Reducing Life Cycle Impacts of the Existing Irish Housing Stock.

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The thesis is submitted in fulfillment of the requirements for the degree of

Doctor of Philosophy

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November 2012

Declaration Page

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Acknowledgement

I especially want to thank my supervisors, Dr Aidan P. Duffy of Dublin Institute of Technology, Ireland and Dr Paul Strachan of University of Strathclyde, Glasgow, United Kingdom for their outstanding supervision guidance and mentoring throughout my research. I also extend my sincere thanks to John Turner (Head of Department, Civil and Building Services Engineering (DIT), all the research members at Dublin Energy Lab and Dr Marek Rebow for all his useful advice during the course of my study.

I also gratefully acknowledge the support of the Sustainable Energy Authority Ireland for providing data for this work. I also extend my appreciation to the Dublin Institute of Technology's ABBEST programme for funding the research.

I also extend my appreciation to Dr Adolf Acquaye for his useful advice on the emissions intensities of the Irish construction sub-sectors.

I also extend my thanks to Dr Lacour Ayompe and Stephen Curran for their support.

Above all, I am very grateful to Almighty God for fulfilling his promises in my life.

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List of abbreviations

APME	Association of Plastics Manufactures in Europe
AIRR	Adjusted Internal Rate of Return
BER	Building Energy Rating
BREHOMES	Building Research Establishment for Housing Model
BREDEM	Building Research Establishment Domestic Energy Model
BREEAM	BRE Environmental Assessment Method
CDEM	Community Domestic Energy Model
CH_4	Methane
CODEMA	City of Dublin Energy Management Agency
CO_2	Carbon dioxide
CO_2-eq	Carbon dioxide equivalent
CSO	Central Statistics Office
CDA	Conditional Demand Analysis
CHP	Combined Heat and Power
DBP	Discounted Payback
DEHLG	Department of Environment, Heritage and Local Government
DOE	Department of Energy
DHW	Domestic Hot Water
DEAP	Dwelling Energy Assessment Procedure
DTI	Department of Trade and Industry
HFCs	Hydrofluorcarbons
EIA	Energy Information Administration
EM	Engineering Methods

ELCD	European Life Cycle Database
EDEM	ESRU Domestic Energy Model
EST	Energy Saving Trust
EC	European Commission
EPBD	Energy Performance of Building Directive
ESRU	Energy Systems Research Unit
EPA	Environmental Protection Agency
EPSIH	Energy Performance Survey of Irish Housing
ETS	Emission Trading Scheme
EU	European Union
FU	Functional Unit
GPP	Green Public Procurement
GHG	Greenhouse Gases
GJ	Gigajoules
GJ/€	Giga Joules per Euro
GWP	Global Warming Potential
HDD	Heating Degree Day
HEM	Housing Energy Model
HER	Heat Energy Rating
HES	Home Energy Saving
IEA	International Energy Agency
INSHQ	Irish National Survey of Housing Quality
I-O	Input-Output
IPCC	Intergovernmental Panel on Climate Change
ISO	International Standards Organization

$kgCO_2$-eq/€	Kilograms of carbon dioxide equivalent per Euro
$KtCO_2$-eq/yr.	Kilo tonne carbon dioxide equivalent per Year
KWh	kilowatt hour
Ktoe	Kilo Tonnes of Oil Equivalent
LCA	Life Cycle Assessment
LCCA	Life Cycle Cost Analysis
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LBP	Life Cycle Building Physics
MAC	Marginal Abatement Cost
MVHR	Mechanical Ventilation with Heat Recovery
NN	Neural Networks
NS	Net Savings
NPV	Net Present Value
MLRA	Multiple Linear Regression Analysis
$MtCO_2$	Million Tonnes of Carbon dioxide
MWh	Megawatt hour
NEEAP	National Energy Efficiency Action Plan
NDP	National Development Plan
N_2O	Nitrous Oxide
NO_x	Nitrogen Oxide
NMVOC	Non-Metallic Volatile Organic Compounds
ODP	Ozone Depletion Potential
OECD	Organisation for Economic Co-operation and Development
PV	Photovoltaic

PHE	Purchased Heat Energy
PE International	GaBi LCA software trade name
PFCs	Perfluorocarbons
PM	Particulate Matters
PU	Polyurethane
REPA	Resource and Environmental Profile Analysis
RES	Renewable Energy Supply
SEI	Sustainable Energy Ireland
SEAI	Sustainable Energy Authority Ireland
SETAC	Society for Environmental Toxicology and Chemistry
SIR	Savings-to-Investment Ratio
SPB	Simple Payback
SWH	Solar Water Heater
SO_2	Sulphur dioxide
SF_6	Sulphur hexafluoride
t	Tonne
TC	Thermodynamic Class
TGD	Technical Guidance Document
UK	United Kingdom
UKDCM	UK Domestic Carbon Model
UNEP	United Nations Environment Programme
UPVC	Un-plasticised Polyvinyl Chloride
USEIA	United States Energy Information Administration
WSA	World Steel Association

Abstract

Despite the importance of addressing the challenges of the 2020 emissions reduction targets of both the European Union (EU) and Ireland, current residential emissions policies have focused mainly on the few existing studies that are primarily used to predict end-use energy and CO_2 emissions savings. To allow all energy and emissions across life cycle phases to be evaluated, a process-based life cycle analysis (LCA) hybrid model was developed with the aim of determining the extent of reductions in resource consumption, greenhouse gas (GHG) emissions and costs of maintaining the existing Irish housing stock.

Thirteen representative archetypes of the pre-1960 – 2002 existing housing stock were developed, and the impacts of each archetype assessed across life cycle phases to give a 'BaseCase' for energy and emissions. Two scenarios for upgrading the housing stock model were analysed – 'meet current building regulations' (Building Regulations standard) and 'meet anticipated future regulations' (Passive House standard i.e. a house that has its operational energy demand as low as practically achievable). This involved identifying and modelling a range of interventions which achieved energy ratings equivalent to the Irish 2010 building regulations and Passive House standards, respectively. These upgraded stock models were then reassessed to estimate their impacts on energy and emissions. Cost evaluations were also carried out for the differing archetype upgrades.

For all archetypes in the BaseCase scenario, results show that operational phase energy and emissions are much greater than for any other phase, representing at least 95.5% in a majority of archetypes. 13% of the life cycle's energy consumption was estimated to come from non-Irish sources. For a majority of archetypes, the weighted

average archetype embodied energy was estimated to be approximately 0.5% of the life cycle energy out of which 29% was estimated as embodied energy due to services (i.e. installation of materials and fit-outs). All retrofit scenarios yield significant operational improvement: primary energy reduced for a majority of dwellings, compared to the BaseCase scenario.

It is estimated that a total of 76MtCO_2-eq and 104.2MtCO_2-eq national life cycle emissions savings compared to 2005 levels can be achieved at positive retrofitting abatement costs of €592/tCO_2-eq and €741/tCO_2-eq in 2020 for the Current Regulations and Passive House scenarios, respectively. A comparison between Current regulations and Passive House scenarios indicated that a total of 21.2MtCO_2-eq national emissions savings compared to 2005 levels can be achieved at retrofitting abatement costs of €1,141/tCO_2-eq in 2020. Detached houses in the Passive House scenario in year 2020 is a good choice for energy efficiency improvement as they represent the highest GHG abatement potential that can be delivered at relatively lowest costs, especially when it is considered that they become more cost effective overtime. This is followed by mid-terraced houses/apartments. Semi-detached houses/end-terraced houses display the lowest GHG abatement at highest retrofitting costs. The effective implementation of this choice will require a combination of regulation, financial support and information/education.

Chapter 1: Introduction

1.1 Background

1.1.1 Depletion of non-renewable resources

The use of fossil fuels has become a predominant source of global non-renewable resource consumption as human activities are strongly dependent on those, especially oil and gas. These fossil fuels used in running traditional energy systems are created by natural processes which have taken millions of years to form, and can be exhausted. The consumption of fossil fuel increased from half a billion tonnes a year from the beginning of the 20th century to seven billion tonnes a year by the 1980's (Pinderhughes, 2004), and fossil fuels remain the dominant source of energy, accounting for over 80% of global primary energy (IEA, 2006). A more recent data from the US Energy Information Administration (USEIA, 2008) shows that the global consumption of fossil fuels increased by over 215% between 1981 and 2006 whilst the EU recorded an increase of approximately 127% during the same period. It should be noted that due to a lack of data on house life cycle energy, the development of this chapter has been based on house operational primary energy use and in cases when this was not possible data on house operational final energy use has also been utilized. Figure 1.1 illustrates the primary fossil fuels consumption between 1981 and 2006 as compared at global and EU levels.

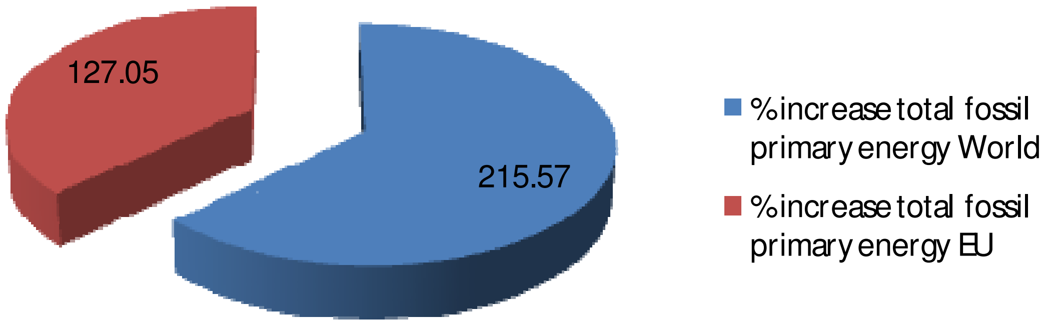

Figure 1.1: Fossil fuel consumption for the period 1981-2006, world and EU compared (USEIA, 2008)

The second most important findings of the scenarios projected by the World Energy Council (WEC, 2007) for meeting the future energy requirements during 2005-2050 indicate that fossil fuels remain the largest proportion of primary energy requirements through the next four decades. Given that the majority of the industrialized countries of the West and the emerging economies in Asia are strongly dependent on fossil fuels, including continued global population rise and increased threat to supply in conflict regions, this dependence on nonrenewable energy resource is unsustainable. For example, up until the Arab oil crisis of the 1970s the issue of sustainability in energy use in industrialized nations was less pronounced (Hammond and Jones, 2008), especially as there was security in the supply as well as stability in the prices of oil. Under the multilateral initiatives of the International Energy Agency (IEA), each Member State has an obligation to have oil stock levels that equate to at least 90 days of net oil imports. The successive IEA total oil stocks in days of net imports (not including figures for net exports such as Canada, Denmark and Norway), represent 131, 145, 145, 143 and 151 oil equivalent in 2008, 2009, 2010, 2011 and 2012, respectively (IEA 2012). These figures represent the last month of each year for which data is available.

1.1.2 Climate change and building activates

Subsequent to years of debate, global warming has now been scientifically agreed to be a result of human activities associated with greenhouse gas emissions (IPCC 2007a). Global GHG emissions due to human activities have grown since pre-industrial times, with an increase of 70% between 1970 and 2004 IPCC (2007a). The main contributor to these green house emissions is the consumption of fossil fuels and flaring of gases whilst global contribution of CO_2 emissions increased from 8,493.6MtCO_2 to 11,219MtCO_2 during the period 1981-2006 (USEIA, 2008). These greenhouse gases are CO_2 - Carbon dioxide, CH_4 – Methane, N_2O - Nitrous oxide, PFCs – Per-fluorocarbons, HFCs – Hydro fluorocarbons and SF_6 – Sulphur-hexafluoride. CO_2 is one of the long-lived greenhouse gases and the most significant anthropogenic greenhouse gas. In 2000, more than 23 billion tonnes of CO_2 were emitted from this source worldwide, 43% more than in the early 1970s. In the field of life cycle analysis, global warming which is an impact category is believed to result in climate change. Global warming is one of the most well-known indicators, and it is a measure of chemical potentials to affect the world's climate (Bare J. and Gloria T. 2005). Carbon dioxide equivalents serve as a basis for comparing the relative input of different emissions to climate change using global warming potentials (Pennington et al. 2004). In terms of potency, carbon dioxide is not the most potent chemical, but it exhibits large absorption in the atmosphere. Using IPCC characterisation factors, a global warming potential, GWP_{100} of 25 means 1 kg of methane has the same cumulative impact of 25kg of carbon dioxide over 100 years.

While global warming is an environmental impact category as well as a mid point indicator, climate change is the end-point category indicator (Bare J. and Gloria T.

2005) associated with a number of effects (IPCC, 2011a). These include precipitation, flooding, storms, less ice, more rainfall, rising sea levels, adverse consequences on both abiotic and biotic elements of the ecosystems, including damage to coral reefs, and a possible average temperature increases by a further 1.4 -5.8 degrees Celsius over the twenty first century (IPCC 2001a). As part of the global community, these impacts will affect Ireland, but it is likely to experience less severe effects. The changes expected to occur include: a 1.5^{o}C increase in winter conditions in Northern Ireland by the 2050s; an approximated 2.5^{o}C increase in July temperatures; marked reductions in summer rainfall by 25-40%; and increased frequency of severe storms over the North Atlantic in the vicinity of Ireland by about 15% (NCCS 2007, pp45). Figure 1.2 illustrates the combination of the six main GHG responsible for global warming.

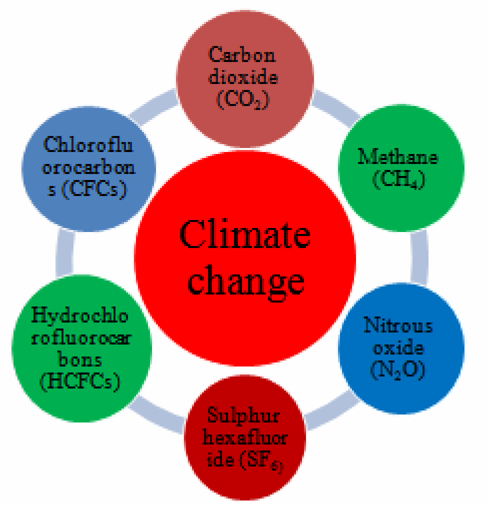

Figure 1.2: Climate change and the six main greenhouse gas emissions

According to IPCC (2007b), to avoid negative consequences of climate change to ecological, social, and technological systems will require timely and appropriate mitigation actions. Strategies to reduce the effect of climate change include sustainable consumption of resources and reducing carbon emissions across all sectors of the economy. The residential sector consumes approximately 30% of global primary energy

(Pulselli et al. 2007). European housing is a predominant element of energy consumption and CO_2 emissions (IPCC, 2001a) as households accounted for 25 % of total energy use in the EU27 in 2007 (EC/OECD, 2008), for 17% in 2003 in Canada (Aydinalp-Koksal, Ugursal 2008) and for 33% in Spain (Labandeira et al., 2006). In the UK, the residential sector accounted for 27% of energy-related CO_2 emissions (DTI, 2003) and for 26.5% with a corresponding 27.1% of energy-related CO_2 in Ireland in 2009 (SEAI, 2009). Figure 1.3 illustrates primary energy consumption as a percentage of national primary energy consumption and as found in literature.

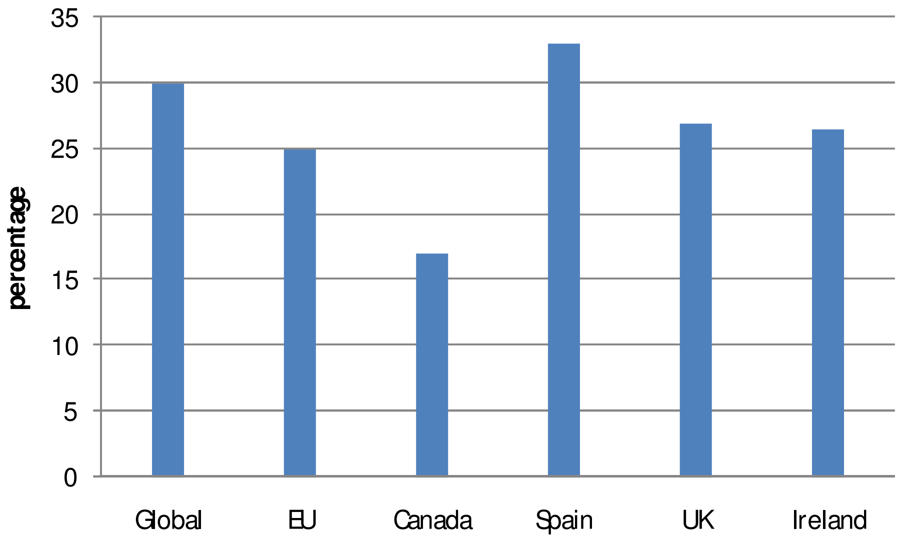

Figure 1.3: Residential primary energy consumption shown as a percentage of national energy consumption and as found in literature

During the period 1980-2005, the residential sector remained prominent in the hierarchy of energy use in Ireland, the total final energy use in the residential sector between 1990 and 2005 increased by 32% (SEI 2007). Similarly, there has been 7.4% and 8.8% increase in residential overall primary energy demand and energy-related CO_2 emissions respectively in 2008 (heat and electricity), despite the country's economic contraction (SEAI 2009). As can be further seen in Figures 1.4 and 1.5, energy consumption in the residential sector has been on the increase since 1990 and remains significant when compared to the other sectors combined.

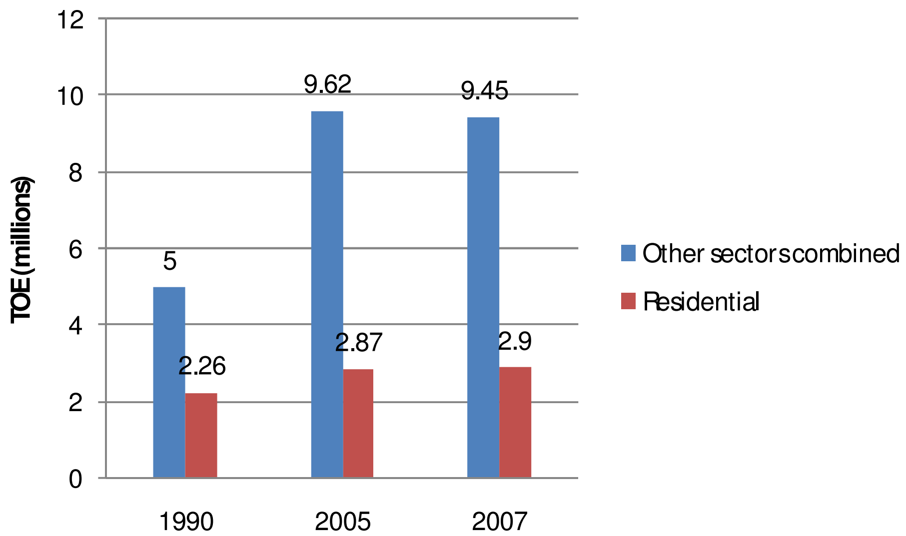

Figure1.4: Total final energy consumption by sector (adapted from SEAI, 2008)

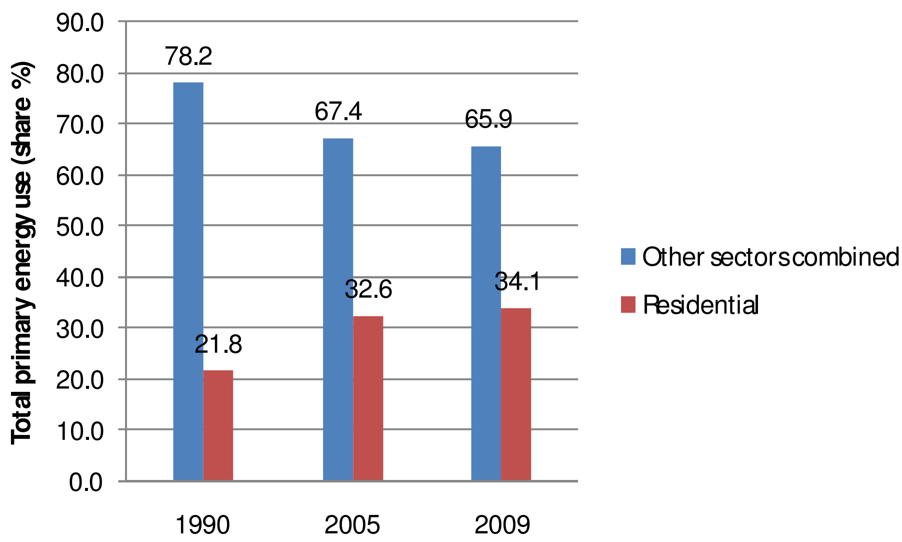

Figure 1.5: Total primary energy requirement by sector and year (adapted from SEAI, 2008)

In Ireland, the main drivers of increased energy use in the residential sector include: 53% increase in the number of houses since 1990; 1.2% increase in dwelling average floor area since 1990 (SEAI 2009); and increase in the penetration of central heating.

Equally, the levels of cavity-walls in Ireland stood at 42%; draught stripping of doors and windows also remained low at 40%; and the penetration of central heating increase was 86% (Healy and Clinch, 2001b). The poor quality of the housing stock has also contributed to the situation where the housing stock was described as being among the least energy-efficient dwellings in Northern Europe (Brophy et al 1999).

Buildings as predominant sources of energy consumption contribute to these emissions because of the energy and materials required throughout their life cycle phases - from the production of building materials through to construction, use and disassembly, energy and other inputs required in material extraction, refinement, fabrication, installation on-site, energy end-uses, (e.g. heating/cooling, lighting, fans & pumps, communications, water heating, domestic appliances), fuel use during building clear out and degradation of materials result in emissions (chemicals) as residual products. These are Carbon dioxide (CO_2), Methane (CH_4), Nitrous oxide (N_2O), Perfluorocarbons (PFCs), Hydrofluorcarbons (HFCs) and Sulphur hexafluoride (SF_6) greenhouse gases as emissions to air, and Nitrogen dioxide (NO_X), Sulphur dioxide (SO_2), Carbon monoxide (CO), Non-Metallic Volatile Organic Compounds (NMVOC) and Air particulate (Dust)/Particulate matter (PM) as air pollutant emissions (indirect greenhouse gases), and are mainly from material processing machinery, transportation, fabrication, (e.g. timber, metals), construction/installation machinery, energy for site excavation, water consumed during construction, lighting, power production by utility companies, material decomposition, transportation, and other construction activities.

In spite of the current downturn in the construction industry globally and in Ireland, it can be seen that the building and construction sector is a significant contributor to socio-economic growth and a key user of natural resource uses in most developed countries including Ireland (Acquaye, 2010). In addition to those main levers of increased energy use previously mentioned, the increased use of energy and natural resources by the housing sector was also driven by use of electricity for water heating, and the occasional use of solid-fuel open fires in central heating (SEAI 2009). For example, use of solid fuel open fire central heating reduced from 31% to 8% and electricity use for heating increases from 1% to 3% during the period 1987-2005 (CSO, 2006).

Concerns about fossil fuels depletion after the 1960s led to global-modelling studies about the impacts of fossil fuels and resource consumption, resulting in predictions of rapid depletions of fossil fuels, including climatological changes due to the world's changing population (Svoboda 1995). Along this continuum emerged the history of the evaluation of environmental impacts of consumer products during the 1960s – 1970s (Guinee et al, 2010) focusing on the comparative environmental advantage of one product over another. For example, mineral glass wool insulation requires less energy and emits less environmental impacts in its production than insulation from polymers. Another typical example is window frame (wooden frame vs. UPVC frame). The recognition by many studies that in addition to the dominance of the operational phase of products led to the conclusion that a significant proportion of the environmental impacts also comes from other processes such production, maintenance, retrofitting and disassembly including all associated transportation. Along this range, the significance of tackling the life cycle of a product /numerous products became a topic of discussion in the 1980s and 1990s (Guinee et al, 2010). Life cycle analysis was one of the results of this discussion. Life cycle analysis is the commonly accepted approach in the compilation of inputs and outputs, and evaluation of cradle to grave potential environmental impacts of a product/numerous products.

In most advanced economies including the emerging economies of Asia, governments encourage the use of LCA in emissions reduction strategies. Houses can be retrofitted in order to reduce resource consumption and the associated corresponding environmental impact. In this way, houses will play a significant role in reducing resource consumption including fossil fuels and greenhouse gas emissions and limiting the effect of global warming. In many of these economies, current building standards ensure that new buildings are highly operationally energy-efficient, resulting in low GHG emissions and environmental impacts relative to older buildings. The greatest challenge in these countries is to upgrade older, less efficient dwellings to higher energy efficiency standards. A life cycle approach, however, should be taken to ensure that the level of refurbishment chosen results in net emissions and energy savings over the projected lifespan of the upgrade.

However, to undertake this analysis will require a combination of two principal approaches: first there is a need for a model that is capable of being used to obtain across life cycle phases a complete view of primary energy and primary energy-related emissions of the existing housing stock (this approach is discussed in Section 1.1.4); and second, there is a need to establish economically and environmentally possible retrofit options (Section 1.1.5 looks at this approach).

1.1.3 Climate change mitigation potential of dynamic stock modelling

In the first approach, to achieve the EU and Irish government targets of 20% reductions in energy and emissions by 2020 will require significant change in our approach to housing stock energy modelling. Dynamic stock modelling - based on housing energy and emissions inflow and outflow characteristics - is a promising tool for exploring future resource consumption and emissions' scenarios in the sector. However, stock modelling methods in current use in Ireland are based mainly on end use energy and do not allow a whole house life cycle assessment of primary energy and primary energy-related emissions. For example, Clinch et al. (2001a) estimate energy and CO_2 savings for Irish housing, and Clinch and Healy (2001b) extended this work to estimate the cost benefit of building stock interventions required to reduce CO_2, SO_2, NO_x and PM_{10} emissions from Irish housing to comply with the 1997 building regulations. However, both studies focus on the impacts associated with the operational stage of a building's life cycle. Reducing the environmental impact of a building based on the delivered energy may not result in reducing life cycle environmental impact (Gustavsson and Joelsson 2010). Therefore, such studies are incomplete since they ignore pre-use, maintenance/upgrade and decommissioning impacts; they are therefore unsuitable for evidence-based policymaking. Stock modelling based on a complete view of CO_2 emissions from the sector will provide additional information directed towards experts from environmental policy.

There are different techniques for stock modelling which can be combined to perform energy and emissions analyses. Process analysis is typified by precise unit process data, mass of materials and energy fluxes, incomplete system boundaries, and excellence in evaluation of advances in technology. Input-output analysis, on the other hand is characterised by economic flow databases, complete system boundaries, a lack of process specificity, balanced data on sectors not easily covered by process analysis, risk of inaccurate results if national economy is mainly import oriented, and risk of inaccurate results if economic flow databases (tables) are not regularly updated. As both input –output analysis and process analysis are limited in their capacity to adequately estimate the emissions associated with retrofitting over the whole life cycle, the two methods can be combined to yield a third method known as hybrid analysis (Suh and Huppes, 2002).

In this study, to allow all energy and emissions across life cycle phases to be evaluated a model of the existing Irish housing stock incorporating a process-based life cycle assessment (LCA) hybrid method, combination of different data sources and energy modelling LCA software tools has been developed. The model incorporates 13 representative house archetypes based on construction details and thermal characteristics of sample houses. It should be noted that the use of archetypes is particularly useful as it provides an alternative approach to individual modelling of each house within a stock by categorising the entire stock into different classes of houses. The results can then be extrapolated by the prevalence of the actual number of houses or total floor area at a national or region or local level (Swan et al 2008).

1.1.4 Climate change mitigation potential of house retrofits

The second approach involves reductions of energy and emissions that are closely associated with the current EU reduction targets. For example, Ireland, under the GHG obligations within the EU, has to reduce its non-EU ETS (Emission Trading Scheme) greenhouse gas emissions by at least 20% below 2005 levels. A reduction of this magnitude will require aggressive programme measures including low and near zero-emissions systems. A strategic energy review, published by the European Commission in 2008 emphasized the need for energy efficiency and making the optimal use of the EU's indigenous resources. Similarly, the National Energy Efficiency Action Plan (NEEAP) for 2009 – 2020 aimed at quantitative estimates of avoided emissions through retrofitting of the existing buildings and enforcement of new building regulations.

The delivery of a new renewable EU Energy Directive covering electricity, heat and transport represent one of the significant features of the EU 2020 climate change package. It aims to provide at least 20% of EU total energy consumption from renewable sources whilst a target of 16% renewable energy is set for Ireland by 2020. It should be noted that these current policy objectives inform why this study focuses mainly on primary energy and primary energy-related GHG emissions reductions. Furthermore, most indicators published by various government agencies focus mainly on GHG emissions reductions.

As the EU and Ireland are already on the pathway to operational near zero-emissions dwellings by 2020 (EC 2010), the main attractive opportunities to mitigate climate change and reduce CO_2 emissions due to dwellings will occur from retrofitting the existing buildings to Current Regulations standard and Passive House standard scenarios. Major retrofit measures that can be applied in the Current Regulations scenario include low emissions systems, such as improving the insulation of envelope elements to achieve a U-value of: 0.16W/m^{2}K for pitched roof insulation at both ceiling and slope levels; 0.20 W/m^{2}K for flat roof; 0.21 W/m^{2}K for walls and ground floors; and 1.6 W/m^{2}K for external doors, windows and roof-lights. Other retrofit measures include improving air-tightness of the building envelope to achieve an air change rate limit of 0.35ac/h. This measure will involve reducing infiltration due to air exchange that occurs through cracks and small gaps in the external fabric of the buildings that are not designed in, such as spaces between window frames and external walls and small gaps around penetrations through the external envelope. All of these effectively reduce significantly the basic air change rate induced by type of construction, e.g. masonry. Heating systems measures that can be applied in the Current Regulations scenario include upgrading all fossil fuel-fired conventional boilers to condensing, instantaneous water heating boilers (90% seasonal efficiency) plus advanced controls for heating systems. Abatement opportunities in the Current Regulations scenario will also occur by: changing domestic hot water (DHW) cylinder insulation from lagging jacket to 50mm factory PU-foam having zero ozone potential and a minimum density of $30kg/m^3$; and provisions of solar hot water heating with a $4m^2$ flat plate systems (powered by grid electricity) plus solar hot water cylinder.

Similarly, in the Passive House scenario, many opportunities for abating CO_2 emissions will arise from zero-emissions systems including greater upgrade of insulation of the envelope elements to achieve a U-value of: $0.1W/m^2K$ for pitched roof insulation at both ceiling and slope levels; 0.12 W/m^2K for flat roof; 0.1 W/m^2K for walls and ground floors; and 0.8 W/m^2K for external doors, windows and roof-lights. Other retrofit measures include greater improvement of air-tightness of the building envelope by substituting existing flues, vents and fans with mechanical ventilation with heat recovery (MVHR). All of these significantly reduce air infiltration from those penetrations that are purpose designed to provide ventilation such as wall vents, trickle vents and open-able windows. Abatement opportunities in this scenario can also come by upgrading the existing heating systems as follows: where there is sufficient land space, all existing condensing, instantaneous water heating boilers are substituted with ground source heat pumps; heating element in the supply air of the MVHR provides additional space heating (Wall, 2006); where there is lack of ample land space, air source heat pumps are provided; and provision of advanced controls for heating systems. Abatement opportunities in the Passive House scenario will also occur by: changing DHW cylinder insulation from lagging jacket to 75mm of PU-foam having zero ozone potential and a minimum density of 30kg/m^3; provisions of solar hot water heating with a 4m^2 flat plate systems (powered by grid electricity); solar hot water cylinder; and photovoltaic systems.

1.2 Research Motivation

In this study, the research motivation is mainly influenced by some of the factors that have been discussed in the previous sections. However, in summary the research motivation includes:

a. Importance of domestic dwellings to emissions – 26% of national emissions in 2007
b. Depletion of non-renewable natural resources including fossil fuels.
c. Increased threat of climate change.
d. Security of energy supply - Ireland's 89% dependency on imported fuels (SEI 2009).
e. The need for cost effective use of resources.
f. Enhanced security of energy supply as proposed in the National Development Plan (NDP) 2007-2013
g. EU and Irish government targets of 20% energy and emissions reductions by 2020.
h. Housing stock considered as among the least energy efficient in Northern Europe
i. The need to identify the best way to retrofitting
j. To obtain the biggest annual savings in avoided energy costs.
k. Tightening of the existing building regulations
l. The Energy Roadmap 2050, which represents the next stage of European Energy Policy, aimed at reducing greenhouse gas emissions to 80 – 95% below 1990 levels.

m. Additional information on imported emissions will be required to drive any policy measures that may be required by countries such as Ireland which largely depends on imports if the EU-ETS is to be extended to the residential sector.

1.3 Research Aim and Objectives

1.3.1 Research Aim

The aim of this study is to determine to what extent energy, emissions and life cycle costs can be reduced by retrofitting the housing stock, and to use these findings to make policy recommendations to mitigate environmental impacts in the residential sector.

1.3.2 Research Objectives

To meet the aim of the study a number of specific objectives have been defined:

- Establish and review previous studies based on housing stock modeling methods, including a critical assessment of the research work used to illustrate the retrofitting of the Irish housing stock, and in cases where such is not available for Ireland, a study from a similar location and region is preferred.
- Develop a hybrid LCA model of the existing Irish housing stock
- Assess across life cycle phases a complete view of the primary energy and primary energy-related greenhouse gas emissions induced by national and international sources. It should be noted that national source of energy and emissions refers to those energy and emissions that occurred within Ireland as a result of interventions in the existing housing stock. In contrast, international source of energy and emissions represents those energy and emissions that occurred outside Ireland due to interventions in the existing housing stock.
- Identify the impact of retrofitting on life cycle performance of the housing stock.

- Identify the optimal energy efficiency retrofit options and their cost effectiveness for the housing stock based on life cycle impacts.
- Identify the proportion of life cycle greenhouse gas emissions induced by non-Irish and Irish goods in retrofitting the existing Irish housing stock.
- Identify what policy measures need to be taken in order to reduce the overall energy use and emissions in the residential sector.
- Make policy recommendations on the best option to retrofitting the housing stock

1.4 General Research Methodology

Further to the brief discussion on the study model in Section 1.1 above, a primary energy and environmental impact model of the Irish housing stock consisting of an archetype model, an energy modelling tool and an LCA software tool is developed. The primary energy and environmental impact model uses a hybrid analysis approach which draws on the advantages of process analysis and input-output analysis based primarily on background data from Ireland (CODEMA and SEAI, 2005), EDEM energy modelling tool algorithms (Clarke et al 2008) and background datasets from GaBi 4.4 software tool (LBP & PE, 2007). A number of new techniques in stock modelling that are investigated and adopted in the framework consist of a bottom-up approach and archetype classification methodology. The hybrid model integrates house annual operational energy (kWh/m^2/yr) as calculated by EDEM/HEM. This is then converted into kg of the respective fuel carrier and energy/emission intensities from GaBi 4 software tool were applied to obtain process operational energy/emissions induced by intervention. Energy and emissions attributable to the installation of retrofitting materials are also derived from Input-output analysis using costs of services (installation of materials and fit-outs), and sub-sector energy/CO_2-eq (carbon dioxide equivalent) intensities coefficients of Irish construction.

To develop a primary energy and environmental impact model of the Irish housing stock, statistical analysis techniques are adopted and used to characterize the housing stock into archetypes by determining the distributions for each household key variable of a sample of 150 dwellings to identify representative parameters; knowledge of housing construction details/building regulations and thermal characteristics to identify corresponding element details; and clustering analysis to identify coincident groups of parameters and element details. The entire pre 1960 – 2002 Irish housing stock was classified into 13 representative archetypes representing the model.

The model was applied to the existing Irish housing stock based on the parameters of the individual archetypes and using EDEM/HEM energy software tool to determine base-case house annual energy use. The outputs of EDEM/HEM were converted into kg of the respective fuel carrier and energy/emission intensities from GaBi 4 software tool were applied to obtain process operational energy/emissions attributable to intervention. Detailed life cycle inventories (bill of quantities) and costs of services were prepared for each of these archetypes. Energy/emission intensities from GaBi 4 software tool were applied to all materials quantities for which process data are available to obtain total emissions (process). Similarly, energy/emission intensities of Irish construction were applied to all material quantities for which only input-out data were available to derive domestic emissions (input-output analysis). By applying percentage shares of national and international arising embodied energy and embodied energy-related CO_2-eq intensities of Irish construction (Acquaye, 2010), energy/emissions results were separated into national and international sources of energy/emissions (process analysis). Energy/emissions due to services were calculated across life cycle phases, using energy and emissions intensities of Irish construction sub-sectors as provided by a previous study (Acquaye, 2010). The impacts due to services are considered national. The total hybrid energy/emissions for a given life cycle phase and the corresponding energy/emissions source were then determined as the summation of international energy/emissions (process analysis), national energy/emissions (process analysis) and national energy/emissions (input-output analysis). A detailed description of the methodology is provided in Chapter 4 of this study

To obtain the impacts of retrofitting the building, a suite of energy efficient retrofit technologies were applied to the building in order to identify the most suitable retrofit scenario and investigate the balance between their impacts across life cycle phases. The above procedures were repeated in succession for each of these archetypes under ‘BaseCase’, ‘meet Current Building Regulations' (2010 Building Regulations) and 'meet anticipated future regulations' (Passive House standard). Then, the results of the retrofitted scenarios were compared to the BaseCase scenario. A comparison was also carried out between Current Regulations and Passive House scenarios.

The model can be applied to evaluate the potential for life cycle impact reductions and economic benefits of different scenarios in the Irish residential sector (i.e. for exploring a number of possible futures).

Relevant policies were then identified based on the model structure and appraised on their efficiency in reducing energy and GHG in buildings using the results from the analysis. The methodology implemented in this study is presented in Chapter 4.

1.5 Main Assumptions

The main assumptions made in the research include the following:

a. In order to evaluate the service life of a building, its service life must be known. In this study a common service life of 50 years for all the buildings within the population has been assumed. This has been considered most appropriate for the following reasons: (1) this is the commonly assumed service life in literature; (2) it will serve as a benchmark for policy making regarding emissions arising from the average dwelling of the housing stock; and 3) using different service lives will put comparison of the results to be on unequal terms.

b. Materials and products used for the refurbishment work were assumed to have service lives based on manufacture's brochures and from other sources, such as Energy Saving Trust (EST).

c. The number of archetypes developed was derived from limited number of sample distributions due to insufficient interactions among the data of the variables of the distribution. The sample distribution can however be updated whenever new data becomes available.

d. It was assumed that house sample is representative of emissions from residential developments in Ireland.

1.6 Contributions to Knowledge

The work reported in this thesis will provide significant contribution to the research field in a number of areas. These include:

a. Global

For the first time, a novel bottom-up archetype technique was developed using: a statistical analysis of the distribution of each household's key variable of a sample of 150 dwellings to identify representative parameters; knowledge of housing construction details/building regulations and thermal characteristics to identify corresponding element details; and cluster analysis to identify coincident groups of parameters and element details. The use of archetypes developed using detailed statistical analysis (multi-linear regression analysis, cluster and descriptive statistics) rather than those developed using the average dwelling approach, allows a more accurate representation of the overall building stock variability in terms of geometric form, constructional materials and operation.

b. National

This study represents the first Irish LCA housing stock model. Moreover, based on the discussion under research motivation above, this study has initiated research in the area of providing additional information on a complete view of the total GHG emissions of retrofitting Irish housing directed towards experts from environmental policy in Ireland. The complete view of emissions induced by retrofitting will be useful if the EU decides to extend the EU emissions Trading Scheme (ETS) to the residential sector.

c. Methodological innovations

The thesis shows how the total process GHG emissions of retrofitting the existing housing stock are disaggregated into two sectors – international and domestic sources, using a hybrid life cycle analysis (LCA) technique. This methodological innovation further underscores the need for a more integrated EU policy on imports. For example, the EU can use the information on imported emissions (international sources emissions) to ensure that the environmental impact of consumption activities do not exceed a sustainable level. Policy measures on consumption of materials, products and components from other countries that are meant for the EU markets can result in significant emissions abatement within the community. Similarly, Ireland can use the information on national emissions to ensure that the environmental impacts of production activities do not exceed a sustainable level. For example, policy measures and energy efficiency upgrades can assist to ensure that the environmental impacts of national consumption and production activities do not exceed a sustainable level.

Furthermore, the thesis shows that archetypes can be developed using the modes of the distribution of the household key variables of energy use. This is in contrast to the most usual practice of using the average U-values based on individual judgments.

1.7 Conclusions to Chapter one

The key conclusions from this chapter are:

- Human activities including use of fossil fuels and gas flaring are responsible for the environmental impact category, global warming.
- Global warming results in climate change which is the end-point indicator of the effect of human activities
- Climate change is still a serious problem and the present level action at national, regional and global levels is inadequate to stabilise the concentration of the six main greenhouse gases in the atmosphere.
- Energy use in the residential sector is a significant source of Ireland's contribution to climate change. Energy use in the sector is rising despite the downturn in the economy and the rate of CO_2 emission reductions is low.

- This thesis proposes a hybrid-LCA model of the existing Irish housing stock that is capable of being used to depict: a holistic view of the energy and emissions associated with retrofitting; the optimal emissions reductions potential; and the best option to retrofitting.
- In order to achieve the 2020 energy and emission reduction targets of both the EU and Ireland, a comprehensible approach is required to address the present trend of increasing emissions between now and 2020, and further than.
- The model presented in this thesis proposes potential emissions reductions from three scenarios as the residential portion of the 2020 emissions reduction targets of Ireland, as well as those of the 2055, which accommodate those emission reductions of the year 2050 in the next stage of the EU energy policy.

1.8 Thesis by Chapters

This section presents the summary of each chapter of the thesis:

Chapter 1 summarises the entire study and includes the following sub-sections: Section 1.1 Background, Section 1.2 Research motivation, Section 1.3 Research aims and objectives, Section 1.4 General research methodology, section 1.5 Main assumptions and Section 1.6 Contribution to knowledge. The chapter provides the background to the entire study by summarizing the causes and the problems that are likely to be caused by climate change. The chapter also outlines the significant contribution of the residential sector to climate change and, in particular the importance of making the sector a part of the solution to mitigation and adaptation of climate change through retrofitting. A proposal is given in the use of process-based hybrid LCA model in stock modelling rather than existing studies based on end-use energy, to optimize the findings of emissions reductions in evidence-based policy making.

Chapter 2 reviews previous studies in relation to existing stock modelling methodologies, environmental accounting techniques, environmental and energy modelling software tools, project evaluation measures and service lives of building products and of complete buildings. A brief account of the existing methodologies in stock modelling, environmental accounting techniques and project evaluation procedures is given, followed by a detailed description of their role in stock modelling.

Chapter 3 looks into the existing Irish housing stock with emphasis on the pre-1960s – 2002 portion of the housing stock which is the subject of this study. The chapter first presents an overview of the existing Irish housing stock by identifying its overall current state and possible future emissions reduction opportunities that are likely to influence future policy. Second, it identifies the main strands from the published national reports and aims to provide some insight regarding the profile of the housing stock. Third, the chapter gives an account of the legislative background of the housing stock. Finally, a number of possible futures are illustrated that are capable of meeting the residential proportion of the 20% energy and emissions reduction targets of the government in the year 2020.

Chapter 4 discusses the hybrid life cycle analysis (LCA) method used in the study. The chapter first presents the overview of the entire methodology and goes on to give detailed procedures of the environmental accounting techniques used to evaluate energy/emissions along process LCA, input-output LCA and hybrid LCA. The chapter also presents the detailed calculation procedures as well as the derived equations. The calculation procedures are first applied to the BaseCase scenario. A wide range of improvement measures to the existing dwellings are then outlined. The calculation procedures are then repeated in succession for the retrofit scenarios. The chapter also looks at the various cost implications.

Chapter 5 presents and discusses the results of the study. The chapter outlines the key findings including detailed explanations of the results of the life cycle assessment, life cycle cost analysis and marginal abatement cost (MAC), of the different house scenarios. Presentation and interpretation of the results in this chapter represents the basis for making recommendations and conclusions in Chapters 6 and 7, respectively.

In some typical studies involving retrofitting of existing housing, findings are expected to be made so that they can support policy making. Chapter 6 makes recommendations directed towards experts from environmental and economic policy, using the findings and interpretation of the analyses that were performed in the previous sections.

Chapter 7 looks at the conclusions and the prospect for future research. The conclusions of the individual chapters are combined and summarised to reach the conclusions of the thesis. The actual reductions in energy, emissions and costs that are possible in retrofitting the housing stock are given.

Chapter 2: Literature Review

2.1 Overview

This chapter starts with a review of literature to identify the main approaches to stock modelling whilst emphasising their strengths and weaknesses. The general methodological approaches are then summarised and an appropriate methodological approach to this study is selected. A more detailed review is then performed of the selected approach, discussing its applications in literature, its strengths and weaknesses.

The literature review was also extended to identify a full set of variables influencing energy use as found in international literature. Subsequently in the chapter, different accounting techniques including software tools and databases used in performing stock modelling based on the selected approach are discussed.

2.2 Existing stock modelling methodologies

Stock modelling refers to the evaluation of the total primary energy use and primary energy-related environmental impacts of a housing stock at local, regional, national and global levels. It can also be used to establish energy supply prerequisites, including the corresponding environmental impacts, and overall requirements of a housing stock of dwellings due to changes in their geometric details or thermal characteristics or operating parameters. Stock modelling is characterised by techniques used in assessing the impacts of policies on emissions in the residential sector**.** In this section, various modelling techniques used for modelling residential sector energy use are reviewed, and the two distinct approaches- top-down approach and bottom-up approach are identified.

A variety of approaches can be used to assess the impacts of policies on emissions from the residential sector. Figure 2.1 illustrates different techniques in modelling methodologies whilst Table 2.1 represents the main characteristics of the two principal approaches.

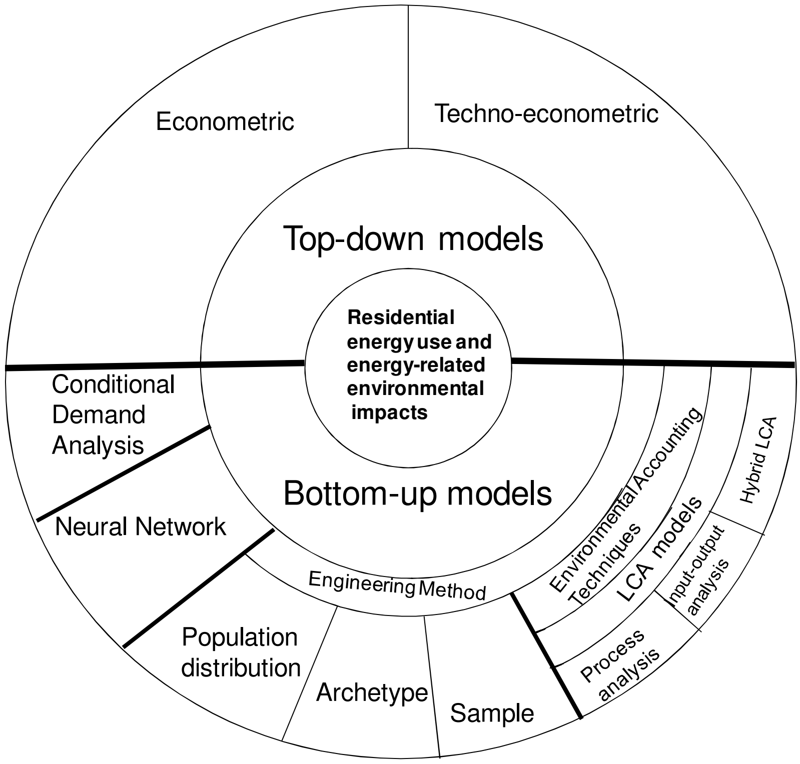

Figure 2.1: Different techniques in modelling methodologies

2.2.1 Top-down approach

Top-down models are statistical models which assess energy supply needs and costs in broad samples of dwellings. They measure the effects of socio-economic and technological features on a local, regional, national or global energy use. In stock modelling, top-down models can be categorized as econometric or techno-econometric (i.e. with input information on household technological components). Top-down models explore energy use of residential sector and other relevant characteristics to relate the energy use to variables of the entire residential sector (Swan and Ugursal 2009).

A top-down approach requires aggregated data and, depending on the type of technique, it is primarily based on input information on demography, employment, trade, growth, investment, tax rates, units of dwellings in the housing stock, house production, export/import, appliance sales, ownership and ratings, goods production, climatic conditions, income and price of variables, within the supply needs. Sources of residential energy data for top-down models include: the preliminary estimate of the total residential sector (aggregated values) as published by governments which compile gross energy values submitted by energy providers (e.g. Ireland - SEAI and USA - DOE/EIA); and the billing records of energy suppliers (e.g. monthly dwelling electricity bill and invoices of purchased heat energy [PHE]).

Top-down models have their strengths in the need for only aggregated data and, in particular their reliance on historical residential records. However, two main drawbacks are identified for top-down models: reliance on historic residential records which renders top-down models incapable of being used to model discontinuous advances in technology; and a lack of detail regarding energy consumption of individual end-uses which removes the ability of top-down models to establish major areas for upgrades for energy/emissions abatement. Therefore, in a situation where deep national emissions reductions are sought, the suitability of a top-down approach for policy knowledge is limited.

Many studies have used econometric models to assess the impact of variables upon energy use- see examples of these studies in Bentzen and Engsted (2001), Siller et al., (2007), Labandeira et al., (2006), Balaras et al., (2007), Canyurt et al., (2005), Nesbakken R., (1999), Mirasgedis et al., (2004), Zhang Q. (2004) and Liao and Chang (2002).

On the contrary, there are few examples of techno-econometric models- see examples of these studies in Saha and Stephenson (1980), Hirst et al., (1977, 1978, & 1980) and Haas and Schipper (1998).

Table 2.1: Main differences between top-down and bottom-up models

Top-down models	**Bottom-up models**
Operate at aggregated level of data	Operate at disaggregated level of data
Ability to model only continuous change	Ability to model discontinuous change
Do not differentiate individual energy uses, rather evaluates the energy use of the entire stock	Evaluate energy use of individual or batch of dwellings and extrapolate the results to represent the local or regional or national based on the representative prevalence of the modeled sample
Simplified calculations	Complex calculations or simulation techniques
Reliance on historical data	Rely on dwelling properties, such as geometry, envelope fabric, equipment, appliances, climate property, indoor temperature and occupancy mode
projections require large longitudinal datasets	projections require cross-sectoral data only

2.2.2 Bottom-up approach

Bottom-up models are statistical and engineering models which assess energy supply needs and costs of individual dwellings towards the combined energy use value of the stock. Bottom-up models can be used to compare buildings and their energy supply systems to gain a detailed perception of production and operation energy alternatives, and assist comparisons between various building and supply systems. A bottom up approach allows the evaluation of the effects of new technologies and potential upgrades, for which top-down methods are less suitable as they rely on statistical data based on historical or current practice (Gustavsson and Joelsson 2010). Depending on the exact technique used, they measure the effects of the geometric details, thermal characteristics and operating parameters on residential energy use of the individual households. Unlike top-down models, these effects can then be weighted by the prevalence of the representative dwellings to represent the locality, region or nation.

Sources of the input data required in bottom up models include information on geometric details, thermal characteristics and operating parameters of the dwellings. Sources of residential energy data include billing data, housing surveys which provides detailed information rather than aggregated values; and “sub-metering” (i.e. consignment of energy metering devices on the large energy consuming appliances within the household to determine both the components of the house energy consumption and their usage profile as a function of time (Knight et al. 2007).

Three main types of bottom-up models have been identified: Conditional Demand Analysis (CDA) technique; Neural Networks (NN) technique; and Engineering Methods (EM) models.

- *Conditional Demand Analysis (CDA):* CDA refers to regression analysis based on the presence of household appliances. It is appliance-specific approach. In comparison to EM models, CDA models are easier to develop and use, and do not require as detailed data (Aydinalp et al., 2002). By regressing total dwelling energy consumption onto the list of owned appliances which are indicated as a binary or count variable, the determined coefficients represent the use level and rating.

Unlike EM models which depend upon assumptions on the time of the first person getting up in the morning, and the period of the house unoccupied during the day, the Conditional Demand Model utilizes observed data on consumer behaviour. For the CDA the input information is a simple appliance survey from the occupant and energy billing data from the energy supplier; and a dataset with a variety of appliance ownership throughout the sample (Swan and Ugursal 2009). The reliability of a CDA technique is dependent on large number of variables.

The use of CDA technique has been performed by few authors - see examples of other CDA based studies in Lefance and Perron (1994), Douglas et al., (1987) and Parti and Parti (1980), Larsen and Nesbakken (2004), Aigner (1984), Caves et al., (1987) and Aydinalp-Koksal M and Ugursal (2008).

- *Neural network (NN)*: Neural Networks are characterized by computing systems, which attempt to model the structure and function of biological neurons (Mihalakakou, et al., 2002). While neurons represent interconnected processing elements, the arrangement of the inter-neuron bonds, including the character of the bonds plays a significant role in establishing the structure of a network. The structures of NN models are characterized by grouping of neurons into layers whilst signals then flow to or from the input and output layers, depending on the structures of the network. Figure 2.2 represents architecture of a neural network system as proposed by Mihalakakou, et al., (2002).

While NN techniques are used in modelling the appliances, lighting, and space heating-cooling energy use in the residential sector, they are not sufficiently flexible to assess the impact of energy conservation measures (Aydinalp et al., 2008). They are static since the prediction model is set in advance using historical data and does not vary when the needs arise (Yang et al., 2005). Literature contains an up-to-dated list of a few of applications of the Neutral Networks technique to housing stock- see examples of these studies in Aydinalp et al., (2002 and 2004) and Yang et al. (2005) and Aydinalp et al., (2003).

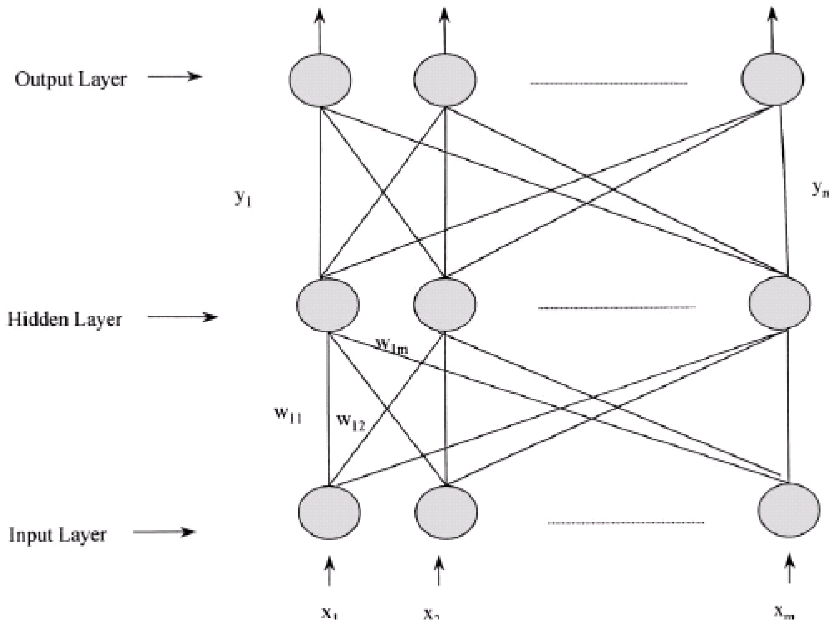

Figure 2.2: Architecture of a neural network system (Mihalakakou et al., 2002)

- *Engineering models:* Engineering techniques are used: to assess energy supply needs and costs of individual dwellings towards the combined energy use value of the stock; and to assess the cost-benefit and marginal cost of carbon abatement for different energy efficient and renewable energy options. They are characterized by developing a representative database of the housing stock. Sources of the input data required in bottom up models include information on geometric details, thermal characteristics and operating parameters of the dwellings. Unlike top down models, engineering techniques incorporate high level of detail and flexibility, and they can fully develop the energy consumption of the residential sector without any historical energy use information. The study identified four EM techniques:

i. *Distributions:* This is an engineering technique based on the distribution of appliance penetration (i.e. number of households using a particular appliance), number of households, appliance ratings and hours of appliance usage to calculate the end-use energy of each household. The end-use energy is evaluated based on the product of the above variables and the inverse of the appliance efficiency. The residential energy use at a local, regional or national level is evaluated based on the combined appliance energy uses. The use of distributions technique has been performed by several authors- see examples of these studies in Kadian et al., (2007), Capaso et al. (1994) and Jaccard and Baille (1996).

   Archetypes: This is an engineering technique which uses taxonomy of a housing stock based on its geometric details, thermal characteristics and operating parameters. The descriptions of each major class of house represent part of the input information required to assess energy supply needs and costs of individual dwellings towards the combined energy use value of the stock and to assess the cost-benefit and marginal cost of carbon abatement for different energy efficient and renewable energy options. The assessed energy use of the individual archetypes is then mapped onto the prevalence of the number of houses best described by each archetype to be representative of the local or regional or national housing stock (Swan et al 2009). The use of archetypes technique has been performed by several authors- see examples of these studies in Johnston et al (2005), Lechtenbohmer and Schüring

(2010), Shimoda et al (2004), Shorrock and Dunster (1997), Boardman et (2005), Firth et al (2009).

ii. *Samples:* While archetypes offer a narrow depiction of the regional or national housing stock due to the limited variety of archetypes that can practically be defined (Swan et al. 2009), samples techniques are characterized by the collection of detailed information of real house samples using on site surveys. These real house samples then become the representative sample of the housing stock. However, it is necessary for the sample to be large enough for it to fulfill that role. The use of samples techniques has been performed by a number of authors:

Farahbakhsh et al (1998) used survey data from 8,767 actual houses to supplement the development of an archetype model of the Canadian housing stock. Based on the generated individual house input file, simulation was performed using National Resources Canada's HOT 2000 monthly bin type building simulation software. A calibration procedure was performed to correct data conversion errors in the input files using energy billing data from 2,524 houses. The national consumption estimate was fond to be in agreement with other studies.

Guler et al (2001, 2008) extended the work of Farahbakhsh et al (1998) to study the impact and economic analysis of energy efficiency upgrades on energy consumption and greenhouse gas emissions (GHG). Their findings show that energy consumption and GHG emissions can be reduced by approximately 8%, 4% and 2% for heating systems, basement insulation and programmable thermostats, respectively. The main upgrades were not found to be economically feasible based on the prevailing energy cost at that time.

Using ERAD simulation engine Larsen and Nesbakken (2004) developed a model of Norway's housing stock using household information from 2,013 dwellings. The major weakness of the simulation engine ERAD was in its high number of numerical inputs, resulting in difficulty in its calibration. The authors estimated unspecified end-uses by their calibration, resulting in a minor overestimation of each end-use contribution. However, the consumption for space heating and domestic hot water (DHW) was found to be approximately 42% and 24% of the total consumption, respectively.

iii. *Environmental accounting models:*

Life cycle analysis (LCA) is the broad methodology used in environmental accounting. LCA aims to provide insights into the potential environmental effects of the complete and detailed systems linked with the provision of buildings or goods and services (Rebitzer et al, 2004). Environmental accounting in an LCA study can be performed using the three main approaches – process LCA, Input-output LCA and hybrid analysis. Details of the three approaches are further discussed in Section 2.3 under environmental accounting methods.

Sources of the input data required in environmental accounting models include background datasets provided by most commercial LCA software, background data based on the inputs of the housing stock and economic input data. The use of environmental accounting in LCA has been performed by many authors – see examples of these studies in Adalberth et al (2001), Scheuer et al (2003), Nemry et al, (2010), Erlandsson and Levin (2004), Gustavsson and Joelsson (2010) and Gustavsson et al. (2010). However, in Section 2.2.4, a more detailed literature review of studies that use LCA techniques to assess a housing stock, are undertaken.

2.2.3 Choice of stock modelling methods

In the previous sections, it has been shown that top-down and bottom-up approaches represent two optional methods to housing stock modelling. However, based on the detailed review of the literature in these sections, it is evident that a number of drawbacks are inherent in top-down models that make them unsuitable for this study. See detail of these as discussed in Section 2.2.1. On the other hand, bottom up models appears to be more suitable for study for a number of reasons. See detail of these as discussed in Section 2.2.2.

Based on this a decision was taken to use a bottom-up model in this study. The remainder of this section discusses some of the main strengths and weaknesses attributable to the individual techniques identified above and justify their inclusion or exclusion.

In Section 2.2.2, it was shown that Conditional Demand Analysis (CDA) models are regression-based which depends on a large number of appliances in the database lack flexibility and detail (Aydinalp-Koksal and Ugursal, 2008). It was also shown that the CDA models rely on observed data on consumer behaviour. It would be recalled that the survey data available for this study contains information only on the average occupancy. Moreover, the number of appliance ownership throughout the house sample is limited as the study considers only the house heating systems, especially as other appliances such brown and white goods can be separated from the building. Therefore this technique can be removed for the purposes of this study.

Similarly, in Section 2.2.2, it was shown that NN models are static models as the prediction model is set in advance based on historic data and does not vary when the needs arise. The present study requires a model that is flexible since discontinuous change in technological advances will be assessed. Moreover a static model is unsuitable for identifying key areas for improvements of energy use. Therefore, the technique also can be discarded for the purposes of this study.

Distributions technique depends on the number of households using a particular appliance, number of households, appliance ratings and hours of appliance usage to evaluate end-use energy of each household. Such level of input data is inadequate to assess the full impact of energy conservation measures. This technique therefore, can also be discarded for the purposes of this study.

The housing database of the present study was assembled between January and March 2005 using a survey such as that used in the sample technique. Sample models represent detailed information of historic records of energy use and other household variables obtained on-site from the individual dwellings. They therefore, permit the capture of the broad range of houses within the housing stock including their ability for use in establishing regions with high energy-energy consumption (Swan and Ugursal 2009). This technique has therefore been selected for use as housing database in this study.

An archetype is a distinct class of house. In a housing stock an archetype is a reprehensive house of a number of the actual dwellings. In stock aggregation, the descriptions of representative archetypes can be used as input data into energy modelling software tools in the assessment of the impacts of a given housing stock. The archetype model is particularly useful in stock aggregation, because they have the potential to support analyses of the existing stock, and, by making assumptions regarding changes in the housing stock and energy retrofit measures, they can be used to make future projections. Stock aggregation can be used to highlight areas where substantial potential exists for improvement in resource use and economic efficiency, enable quick what-if analyses, allow policy makers to optimize regulations and market incentives to achieve specific targets, and analyze how policies in one area (such as energy security or housing affordability) can affect other impacts from buildings (such as air pollution or energy demand), and develop priorities for research and development (IEA 2001). Scenarios of possible futures developed for a housing stock through use of archetypes can be used by governments and other stakeholders as a basis for strategic planning (Natarajan and Levermore, 2007). This technique has therefore been selected for use in this study.

LCA technique provides a broad methodology in environmental accounting, and in particular as it presents insights into the potential environmental effects of the building system across life cycle phases. The LCA approach has therefore been selected for use in this study.

On the basis of the above, a bottom-up model incorporating LCA and archetype approaches has been selected for use in this study. Therefore, in the next few paragraphs a more detailed literature review of archetype and LCA techniques are undertaken.

2.2.4 Previous studies of bottom-up models

Archetype technique

A number of authors have attempted to evaluate the energy and environmental impacts attributable to different housing stocks over various time periods using bottom-up methods (Engineering models [archetypes]). These models are those that have been performed at regional, national and local levels. The models vary in their level of detail.

The house archetype approach has been used by a number of authors to model energy and resource quantities and impacts, from a study at a regional level by Lechtenböhmer and Schüring (2010) to more recent studies at urban scales by Firth et al. (2009) and Shimoda et al., (2004). The emergence of many energy and resource reduction models driven by the need to support the assessment of emissions mitigation policies in the UK residential sector has been demonstrated by the BREHOMES model (1997), the 40% house project (2005) and the model developed by Johnston et al. (2005) (henceforth referred to as the Johnston model).

The number of archetypes used in published research varies from as few as two to several thousands, and often data from actual buildings rather than most relevant variables associated with energy consumption, are used. It should be noted that in as observed from literature the usual practice of selecting key variables of energy of housing stock in the development of archetypes is based on individual judgments. For example, Firth and Lomas (2009) developed 47 archetypes of the housing stock of the city of Leicester, UK using age of dwelling and built form as the key variables of energy use. Age of dwelling was selected because it a key variable of energy use since older dwellings are constructed to lower thermal standards. Similarly, built form was selected because it determines the number of exposed walls and the average floor area. However, in the case of the age of the dwelling, it should be noted that there are instances when households have carried out energy efficiency improvements in their houses over the years. These will be in contrast with the age of these dwellings. Similarly, two houses belonging to the same built form may have different construction details e.g. a solid wall vs. a cavity wall. Their energy use will be different. A further discussion within this context and a detailed review of previous studies regarding the development of archetypes is provided in the following paragraphs.

Lechtenböhmer and Schüring (2009) used only two archetypes. Their simulation of the entire residential buildings provides a database of the building stock by construction periods, building types, as well as typical building sizes. Using typical U-values of façade, roof, floor and windows, they evaluated the country specific energy demand for space heating per square metre for the three climate zones**.** While admitting significant uncertainties resulting from the lack of precise statistical information of the characteristics of the EU building stock, the authors still provide rough quantifications of the potential, appropriateness and cost of relevant strategies for improving the quality of the building shells of residential buildings in the EU.

Shimoda et al., (2004) developed a residential energy use model for Osaka city, based on 43 variables- 20 dwellings (ten types of detached houses and ten types of apartments) and 23 household types (occupancy pattern). The dwellings have identical insulation levels based on 1997 commercial offerings, and were modelled using conductive heat transfer analysis. While the individual archetypes were simulated and multiplied by the number of dwellings they represent, but the results indicated that total estimated energy use is less than measured values which they ascribed to surveys' error of overestimation for single or two people families in larger cities, rather than for the usual household with more than three members.

Firth and Lomas, (2009) developed the Community Domestic Energy Model (CDEM) of the 2001 English residential housing stock, and using 6 built form categories and nine age built categories, resulting in 47 archetypes. However, in their model, authors excluded the pre 1900 purpose-built flats and post 1945 other flats because such combinations occur very infrequently in the housing stock. Built form characteristic was selected as it represents a key factor in space heating, and in particular determines the number of exposed walls and the average floor area (both of which affect the dwelling heat loss). The authors used a weighted average dwelling approach to model space heating dwelling annual energy and CO_2 emissions for each archetype using the monthly analysis programme (Building Research Establishment

Domestic Energy Model [BREDEM-8]). However, their models' annual gas consumptions for mid-terrace, semi-detached and purpose-built flats are slightly below the lower 95% confidence interval for English House Condition Survey measurements, which the authors attributed to a combination of assumptions and inaccuracies in the modelling process as well as the effects of sampling and measurement errors in English House Condition Survey itself.

Johnston et al (2005) employed just 2 archetypes, which are assumed to be representative of pre- and post – 1996 of the existing UK housing stock, respectively. Natarajan (2006) had earlier put forward that the technique may not result in suitable distributions, due to the absence of historical inter-relationships that exist in a relational stock model. The authors justified the selection of the two archetypes on the basis that: first, background data and their projection on insulation and appliances and stock replacement series, are only available at the level of the whole housing stock; and second, at the overall stock level, the impact of dwelling type on energy use and CO_2 emissions is marginal, when compared with the impact of the thermal characteristics of the fabric of the building envelope and heating system efficiencies. Their model consist of a data module (including information on various energy-related variables of the UK housing stock), and a BREDEM based energy and CO_2 emission calculation module. Similarly, the authors used a weighted average dwelling approach to perform energy analyses. This is because the authors preferred average performance values of a wall, a roof, a space heating system and a lighting system across the stock to the individual differences in geometry, thermal performance and energy use of the individual dwelling types. The model was used to develop a number of detailed illustrative scenarios of the UK housing stock for each of the two archetypes. The authors projected that the UK would achieve 80% emission reduction target in the year 2050 using currently available technology. However, this is disputed by another study by Natarajan and Levermore (2007b), and the discrepancy may be the result of the intrinsic simplifications made in Johnston's model.

The BREHOMES (Shorrock et al. 1997) is a physically based model of the energy use of the UK housing stock for a given year consisting of 1,000 archetypes Shorrock et al. (1997), an energy modelling software (BREDEM) and a number of data sources. The main source of data is a regular survey undertaken by a market research company, from which inputs for U-values of the main elements of the buildings and heating systems efficiencies are estimated. The authors developed two scenarios for the energy use and carbon dioxide emissions of the UK housing stock these include 'Reference scenario' and 'Efficiency scenario' - the uptake of a number of energy efficiency measures (i.e. based only on currently available technology). The author's main reason for limiting the second scenario to currently available technology is informed by the need to keep projections of energy efficiency scenarios as realistic as possible. The authors used a weighted average dwelling approach to evaluate emissions savings for the UK housing stock and their findings show that the Efficiency scenario presents approximately 21MtCO_2 (13%) savings in the year 2020 relative to the Reference scenario. The reference scenario also shows approximately savings of 13% in CO_2 emissions relative to 1995 housing stock CO_2 emissions.

The UK Domestic Carbon Model (UKDCM) 40% house project model (Boardman et al. 2005) employed 20,000 dwelling types as representative dwellings of the UK 1996 housing stock and beyond i.e. to year 2050. The formation of archetypes was based on variables the authors considered important in house energy use in UK housing. The 20,000 archetypes were derived from the disaggregation in the UKDCM model, representing 9 regions, 12 age classes, 10 dwelling types, 6 tenure types, 4 classes for number of floors and 6 construction details. The main source of data for the UKDCM model is the various House Condition Surveys of the countries within the UK. Other sources of data include sub-models for cooling, heating, lights & appliances, and heating & hot water system demands. Heating and cooling demands were modelled using fuel conversion technologies and systems efficiencies. Similar to the other three models earlier discussed, the authors used a weighted average dwelling approach to perform energy and emissions analyses. Their results show that the UK could achieve 40% emissions reductions in the year 2050 relative to the 1996 baseline year.

Unlike the above studies, Clarke et al. (2004) developed thermodynamic representative house classes for simulation based on the main determinants of energy use within the Scottish housing stock. The authors used the following values or levels of insulation level (6), capacity level (2), capacity position (3), air permeability (3), window size (3), exposure (5), and wall to floor area ratio (2), resulting in 3240 classes. Using the building performance simulation software ESP-r, each class was modelled to determine the thermal energy requirements. The total energy use of each class was assessed by applying heating system information such as heating/cooling, ventilation, DHW, and lighting. The results were then summarised within a web-based energy modelling tool for comparative analysis and assessment of the impact of upgrade options upon the Scottish housing stock.

Regrettably, there are a number of drawbacks linked with the models developed by Lechtenböhmer and Schüring (2009), Shimoda et al., (2004), Firth and Lomas, (2009), Johnston et al (2005), Shorrock et al. (1997) and Boardman et al. 2005 which make inappropriate for this study. A major limitation of these works is is the use of average dwelling techniques rather than modes ("typical values") of the distribution of the variables to predict energy and emissions reductions. The use of modes of the distribution is expected to be more representative as it represents the centre of the distribution. Using the modes will therefore truly describe an archetype, which is a representative house consisting of a number of houses at a local, regional, or national level.

Another major limitation of the works is the absence of clear data for some construction details within the various House databases used in the models. For example, insulation averages were estimated from Great Britain averages to represent the UK averages (Shorrock and Utley, 2003). In addition, a lack of clear detail of previous upgrades regarding the housing stock is also a limitation in these works. For example, two separate houses, each representing the same age group, may have considerably different energy use patterns due to different levels of retrofit measures applied in the past (this time not necessarily a result of the prevailing building regulations, but a result of factors, such as household income, awareness, tenure, life style, comfort and so on). The energy use of such houses grouped under the same age class with those not retrofitted will be different. All of these may have suggested why small differences exist between the results of the UKDCM 40% House and the BREHOMES models when compared the same scenarios run in another model – the DECarb model (Natarajan and Levermore 2007b). It should be noted that while the predictions of Shimoda et al. (2004) and Firth and Lomas (2009) are less than measured values, the work of Lechtenböhmer and Schüring (2009) only provides rough quantifications for energy and emissions.

A major limitation with the work of Clarke et al (2004) is in the large number of archetypes. It would be recalled that a large number of archetypes would make description, stock analysis, and the assessment of new scenarios difficult (IEA, 1998), As indicated from the above discussions, it is clear that the models developed by Lechtenböhmer and Schüring (2009), Shimoda et al., (2004), Clarke et al (2004), Firth and Lomas, (2009), Johnston et al (2005), Shorrock et al. (1997) and Boardman et al. 2005 include a number of important limitations that preclude their use within this thesis. The principal significance of these is their use of average dwelling approach to predict energy and emissions. For this reason a robust methodology has been proposed in the development of archetypes, which incorporates a review of international literature to identify the full set of housing stock variables which impact energy use; perform an empirical assessment of the importance of these variables on the Irish housing stock by undertaking a statistical analysis of an Irish housing database containing energy use and detailed household variables; and the development of representative archetypes based on the prevalence of the full set of key housing variables in Irish housing stock.

Similarly, the technique used by Clarke et al (2004) cannot be fully implemented in this study, considering the resulted large number of archetypes. It should be noted that models which categorised national housing stock into representative archetypes based mainly on the representative parameters that are modes of the distribution of key variables are not reported in literature.

Housing stock studies based on LCA techniques

Nemry et al, (2010) developed a model of the building stock for the EU-25 based on 72 building types of which 53 are existing buildings and 19 buildings are new. The building stock was further categorised into three dwelling types – single-family houses (including two family houses and terrace houses); multi-family houses; and high-rise buildings. The authors performed a detailed literature review in order to determine for each building type a typical representative building model with corresponding construction, used materials and masses. The authors obtained construction details for all climatic regions in the EU-25 from European Project: Energy Performance, Indoor Environment Quality, Retrofit (EPIQR 1996) and Jaggs and Palmer (2000). Data on the life span of the materials and the actual state of the buildings at the time of the study was obtained from INVESTIMMO (Bauer et al 2004) and the European COST, respectively. The authors merged similar building types defined in two different countries into one building based on the same climatic conditions where comparable and when the materials and techniques used for the building are comparable. The long-term heating degree days (HDD) of each country based on the period 1980-2004 was used to represent heating in the EU-25 for similar zones in order to ensure comparable climatic boundary conditions. Overall, all background data except heating energy are European datasets. Background datasets were taken from an LCA software, GaBi 4 databases whilst additional datasets were modelled using the same boundary conditions and by applying the same modelling methodology. The authors used a service life of 40 years for new buildings and a service life of 20 years for old buildings.

Using the above information, the authors calculated life cycle impacts of the building types in the BaseCase option for space heating only. Three upgrade options were identified for each of these building types and their life cycle impacts were reassessed using the parameterized model initially developed in GaBi software. Results show that the operational phase remains dominant for all building types. All three upgrade options yield a significant environmental improvement potential, which for a majority of building types represent at least 20% compared to the BaseCase option. The results further suggest that the main improvement potentials at EU level rest with single family houses.

Erlandsson and Levin (2004) developed a model consisting of one multi-dwelling house located in Stockholm assumed to be a representative for all Swedish multi-dwelling houses built during the period 1940 to 1998 and beyond, and an operational energy modelling tool (ENORM 1000). The house has one of the common designs from the "Million Homes" programme and located in an area with other almost identical houses. The energy use in the house was monitored by monthly meter readings of district heating, cold water and electricity to operate the house. The life span of the building was assumed to be 40 years and the overall payback period of the project was determined to be 35 years. The system boundary of the study comprises pre-use, retrofitting and maintenance (i.e. installation of a urine separation system for use as fertilizer on a nearby farm). The actual maintenance of the buildings by replacing materials at the end of their service lives including maintenance of boilers were not included. Similarly, the disassembly phase of the building was omitted.

Using life cycle approach and a calculation based on back-casting technique, the authors evaluated BaseCase and retrofit options operational energy for heating, ventilation and electricity usage. Using a weighting method based on Swedish quality norms, the authors aggregated the environmental profile from the LCA and give an internal relation between different impact categories. The authors concluded from the assessment that retrofitting was an environmentally better choice than the construction of a new building, on the condition that the same essential environment related functional performance is attained. Their findings of potential environmental impact reductions of approximately 70% for the heating service and 75% for the waste water system are achievable and in agreement with national estimates, on the condition that the suggested measures are performed.

There are several limitations associated with the models developed by Nemry et al., (2010) and Erlandsson and Levin (2004) which make them not fully appropriate for this study. A major limitation of the work of Nemry et al., (2010) is the use of the long-term heating degree days (HDD) to represent heating energy use for each country based on similar climatic zones. This is likely to result in ambiguity in the final results. For example, countries, such as France, Italy, Greece, Cyprus, Malta, Portugal and Spain grouped under zone one have different national climatic zones as distinct from one another. Furthermore, it should be noted that Greece has four distinct climatic zones.

The work of Erlandsson and Levin (2004) shows a major limitation as it uses only one multi-dwelling house located in Stockholm to represent the entire multi-dwelling houses in Sweden. This is also likely to lead to error in the final results. This is particularly so as the other multi-dwelling houses in other locations are likely to have different construction details. Other characteristics that are also likely to be different include heating systems, air change rate and previous upgrades. Overall, a common limitation of these works is the level of their system boundaries. Erlandsson and Levin (2004) did not fully evaluate the life cycle energy and greenhouse gas emissions attributable to the housing stock; for example, the authors did not evaluate either the contribution of fuel supply chains to energy and emissions processes (such as exploration, extraction, refining, and transport) and services (such as the installation of materials and fit-outs, and maintenance of appliances e.g. boiler, etc). Similarly, the work of Nemry et al., (2010) did not include the impacts attributable to maintenance of appliances.

However, a main significance of the work of Nemry et al., (2010) is the use of European datasets as background data. Another main worth is the use of generic parameterised models which makes analysis less cumbersome including reduced time. Similarly, the technique used in modelling additional datasets to supplement those from GaBi 4 appears to be useful. All of these techniques can be adapted and utilised in this thesis.

As indicated from the above discussions, it is clear that the models developed by Nemry et al. and Erlandsson and Levin (2004) include a number of important limitations that preclude their full use within this thesis. The principal significance of these is the limitation of their system boundaries including the over simplification of the model of Erlandsson and Levin (2004). For this reason a robust model has been proposed in the evaluation of a complete view of energy and emissions of the existing Irish housing stock. It consists of an archetype model, an energy modelling software and a life cycle analysis (LCA) software.

It should also be noted that models which fully evaluate the life cycle energy and greenhouse gas emissions of national housing stocks are not reported in literature. Studies either omit certain life cycle phases or important upstream inputs; for example, none evaluated either the contribution of fuel supply chains to energy and emissions processes (such as exploration, extraction, refining, and transport) and services (such as the installation of materials and fit-outs, and maintenance of heating/ventilation appliances). It would be recalled in Section 2.2.2 that the model developed by Erlandsson and Levin (2004) covers only one multi-dwelling house in Stockholm, which assumed to be representative for all multi-dwelling houses constructed during the period 1940 – 1998 and beyond, of the existing Swedish housing stock. Complementary literature reviews of the different archetype bottom-up modelling techniques can be found in Swan and Ugursal (2009) and Kavgic et al., (2010).

2.3 Environmental accounting methods in LCA

In the previous section, the two distinct approaches to stock modelling (top-down and bottom-up) were discussed. It was decided that a bottom-up archetype technique (archetype approach) based on environmental accounting LCA will be most suitable to estimate the primary energy and primary energy-related emissions of the existing Irish housing. There are three main approaches to carbon accounting in LCA: Process-oriented analysis; Economic input-output analysis; and Hybrid analysis (Suh and Huppes 2002) (see Figure 2.3). The remainder of this section is organized as follows: In Section 2.3.1, the general methodological framework of LCA is discussed. Next, process-oriented analysis; economic input-output analysis; and hybrid analysis are presented in Sections 2.3.2, 2.3.3 and 2.3.4, respectively.

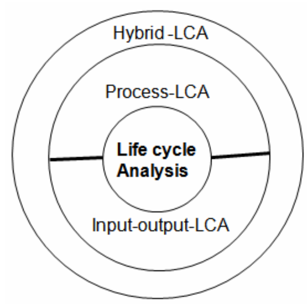

Figure 2.3: LCA techniques

Background

Life Cycle Analysis (LCA) based on primary energy is significant to minimise resource uses, GHG emissions and costs. The development of Life Cycle Assessment (LCA) has been emergent over the past five decades. Concerns about fossil fuels depletion after the 1960s led to global-modelling studies about the impacts of fossil fuels and resource consumption, resulting in predictions of rapid depletions of fossil fuels, including climatological changes due to the world's changing population (Svoboda 1995). This resulted in increased interest in performing more detailed energy calculations on industrial processes (Meadows et al. 1972) – as by the US Mid West Research Institute (and later, Franklin Associates) which carried out an LCA study in 1969 for the Coca Cola Company to determine which type of beverage container had the lowest releases to the environment and made the fewest demands for energy and resource consumption (Stilwell 1991). The intervention of the US Environmental Prevention Agency in the 1970s saw to the improvement of this initiative, resulting in the creation of an approach called Resource and Environmental Profile Analysis (REPA) (Hunt R 1992). Life cycle logic which was first incorporated into the method of risk management in the late 1970s and early 1980s, soon became the "slogan" in the US public policy community to develop environmental protection standards (Stilwell J 1991) and to more recent initiatives such as Blue Angel, Green Cross, and Green Seal which use and continue to improve LCA for the purpose of product labelling and evaluation.

Since then, LCA has been adopted by increasing numbers of corporations, non-profit organizations, and National governments as an aid to understanding the environmental impacts of their actions. LCA is now under the general guidelines of ISO 14040, 2006 and ISO 14044, 2006 (ISO, 2006).

2.3.1 The structure and components of LCA

Life cycle analysis is the methodology used in evaluating the resource use and environmental impacts of a building across its life cycle phases. LCA is a broad method for evaluating the full environmental contributions of a building. Based on the description by the Society of Environmental Toxicology and Chemistry (SETAC), the methodological framework for an LCA study comprises: goal and scope definition, inventory analysis, impact assessment and improvement assessment. LCA is conducted by defining building systems as models that describe the key elements of physical systems (ISO 14040, 2006). An LCA of a building looks at its full life cycle i.e. from cradle to grave. Life cycle refers to the interconnected phases of a building system and incorporates: pre-use phase (i.e. extraction/mining, refinement, processing, manufacture of products and materials, actual construction of the building, and all associated transportation), use phase (use of the building, maintenance and repair) and final disposal/end-of-life phase (detaching reusable products and materials, demolition of the building, and all associated transportation).

In recent times the "International Standards Organisation (ISO 14040, 2006): Environmental Management - life cycle assessment - Principles and Framework" was released which describes four principal components of an LCA as: goal and scope definition, inventory analysis, impact assessment and interpretation of results (ISO 14044, 2006). Furthermore, life cycle interpretation has been brought into the methodological framework, and represents the phase that interacts with all other phases in the LCA. It should be noted that the ISO 14040, 41, 42 and 43 were 'rolled up' into the above two standards. Figure 2.4 below indicates the various phases in the life cycle of a building and application of a life cycle assessment.

Goal definition and scope

The goal and scope definition is the first phase of LCA and establishes why the LCA is being conducted and its intended use, as well as the system and data categories to be studied.

Aim of an LCA

In general the aim of an LCA is the improvement of the application being considered.

Scope

The scope of a life cycle assessment study of a house should be sufficiently well defined to ensure that the breadth, depth and detail of the study are compatible and sufficient to address the stated goal (ISO14040:2006. The scope is dependent on the goal of the life cycle assessment and encompasses: building system to be studied; the functions of the building system or in the case of comparative studies, the building systems; the functional unit; the system boundary; allocation procedures; impact categories selected and methodology of impact assessment, and subsequent interpretation to be used; assumptions; limitations; initial data quality requirements; type of critical review, if any and type and format of the report required for the study; and data requirements.

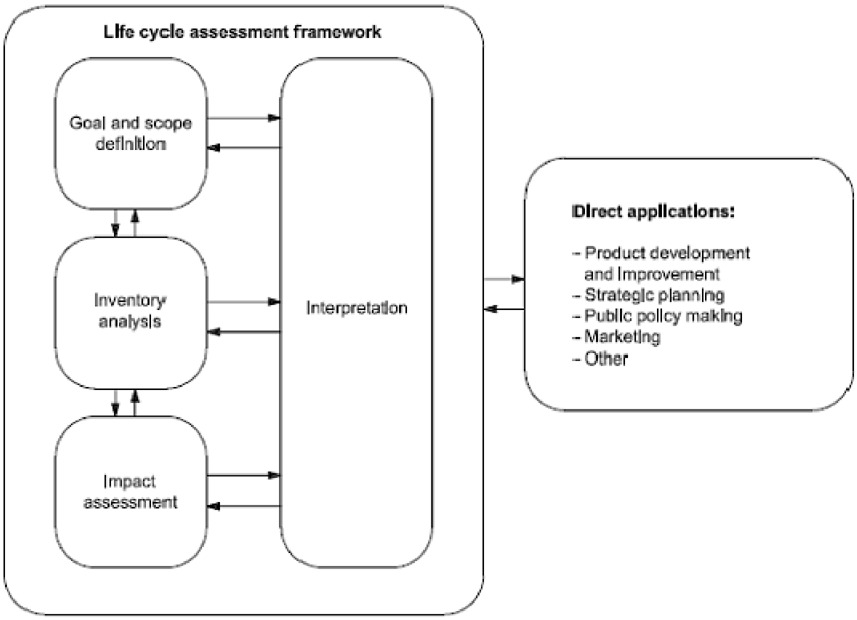

Figure 2.4: Stages and application of an LCA (ISO 14040, 2006).

Functional unit (FU):

To perform the life cycle assessment of the buildings, a functional unit has to be selected. The primary purpose of a functional unit is to provide a reference to which the inputs and outputs are related (ISO 14040, 2006). Such a reference can be used to ensure comparability of the life cycle inventory (LCI) results and, in particular when different building systems are being assessed, to ensure that such comparisons are made on a common basis. Furthermore, a functional unit is also to provide a reference for which policy making is related. Such a reference can be used, for example to assist policy makers to decide which category of buildings needs to be renovated or be given priority within the available financial resources.

The selection of functional units in life cycle studies has been discussed in several previous studies. Nemry et al. (2010) assessed option to reduce life cycle impacts of EU buildings and explored the use a functional unit $1m^2$ of the building's living area over the period of one year. Adalberth et al. (2001) estimated life cycle impacts of four multifamily buildings in Sweden and adopted the functional unit 'm^2 usable floor area', because such a functional unit would result in easier comparison between the buildings. For the purposes of standardization, together with the need to avoid arbitrary selection of function unit, Blengini (2009) assumed a functional unit of $1m^2$ net floor area of the building over a period of 1 year.

Life cycle inventory (LCI) databases

There are several commercial, industrial and publicly funded projects databases that cover commonly used goods and services. Public database initiatives include publicly funded projects, and national-level projects databases. There is also formalised bilateral cooperation between the United Nations Environment Programme (UNEP) and several national-level database development initiatives across the globe. These include EU, Italy, Japan, Brazil, Thailand, Malaysia, China, and Germany. Several of these countries also involve in joint initiatives and international partnerships in many countries. The EU

Platform on LCA also established cooperation with many of these countries and the UNEP.

There are data collected and made accessible for use in LCAs by industry sectors. They provide primary data which are those obtained from specific facilities as a primary source of information; the data is measured or evaluated for a particular facility. Several examples of such sources include the Association of Plastics Manufactures in Europe (APME); and Environmental profile for the European aluminium industry. Table 2.2 below indicates various database initiatives.

There are several commercial databases used for environmental evaluation. These include GaBi 4.4 Professional, SimaPro database, Ecoinvent data, Umberto and the Boustead Model 5.0. References to these databases are in the reference section of this thesis. It is important to be knowledgeable about these databases in order to understand the relevance and applicability to the study. For example, most LCA commercial software come with embedded databases as well as additional databases from industry including those earlier mentioned. In cases when certain datasets are unavailable within the LCA software, additional datasets can be modelled based on other industry information and should be cross-checked with literature data.

Table 2.2: Indicative, non-exhaustive list of databases

Database		
Publicly funded projects, National LCA projects, and Joint initiatives and International partnerships	**Commercial**	**Industry-based**
Germany (http://www.fzk.de/) Developer of NLZ Germany database	GaBi 4 database by PE International of Germany. When purchased, it is delivered with a generic database by default	Association of Plastics Manufacturers in Europe (APME)
Japan: National LCA projects of Japan - coordinated by the Japanese Environmental Management Association for Industry (JEMAI)	BRE Building Research Establishment Ltd - Watford (United Kingdom) (http://www.bre.co.uk/) Developer of BREEAM. When purchased, it is delivered with a generic database by default	International Iron and Steel Institute: LCA of the steel industry
Thailand: Thai national LCA project and network; coordinated by the National Metals and Materials Technology Centre (MTEC);	(Denmark) (http://www.lca-center.dk/) Developer of EDIP.	Environmental profile for the European aluminium industry
China: National LCI data collection, EPD and standardization activities, coordinated by the China National Institute of Standardisation (CNIS);	Ecoinvent database	FEFCO European database for corrugated board-life cycle studies
Malaysia: Malaysian National LCA database project	CML Institute of Environmental Science, University of Leiden (The Netherlands) (http://www.leidenuniv.nl/cml/) Developer of CMLCA	NIDI (Nickel Development Institute), life cycle assessment of nickel products, Final report prepared for Nickel Industry LCA Group, Eco-balance, 2000
Brazil: the Brazilian IBICT as the coordinator of the National LCA database projects in Brazil	ENEA – Bologna (Italy) (http://www.enea.it/) Developer of EcoSME	The Network for Transport and the Environment, NTM www.ntm.a.se

Database		
Publicly funded projects,	**Commercial**	**Industry-based**
The International Life Cycle Data Network (ILCD) expected to provide decentralised access to LCI datasets by the end of 2009. It is a network of consistent quality-assured LCI data sets - from industry, national LCA projects, research groups, and consultants;	IVL Swedish Environmental Research Institute – Stockholm (Sweden) (http://www.ivl.se/) Developer of LCAit.	(1) Generic LCA data for electricity for EPD based on IEA energy mixes and ETH LCI data (2) These data could also be compiled from the origin sources: http://:www.cpm.chalmers.se http://:www.energieforschung.ch.
UNEP/SETAC life cycle Thinking	LBP University Stuttgart (Germany) (http://www.ikpgabi.uni-stuttgart.de/)	ICDA (International Chromium Development Association), 2001. http://www.jernkontoret.se
The EU Platform on LCA in cooperation with UNEP and other National LCA Database projects. Developer of ILCD	PRé Consultants – Amersfoort (The Netherlands) (http://www.pre.nl/) Developer of SimaPro.	IMOA (International Molybdenum Association). http://www.jernkontoret.se
Finnish LCA database for energy, LIPASTO	LCA Center Denmark c/o FORCE Technology – Lyngby	For Pit coal: Nickel Development Institute Canada. http://:www.cfd.rmit.edu.au.
Swiss Agency for the Environment, Forest and Landscape	BUWAL	
	DEAM TM	
	The Boustead Model 5.0	
	Franklin Associates	

Life Cycle Impact Assessment (LCIA)

In the previous section, the process of an LCI including the various available databases was discussed. In this section, an overview is provided of the models and methodologies for calculating and cross-comparing indicators of the potential impact contributions resulting from resource consumption, emissions and wastes emitted in the provision of a building.

Unlike the LCI which is a well established methodology in LCA, life cycle impact assessment (LCIA) methods are still less defined as there is no agreement on the best methodology to be applied (Guinee J.B., 2002; Scheuer, et al., 2003; Blengini, 2009). Life cycle impact assessment is the third phase of Life Cycle Assessment (LCA) aimed at comprehending and assessing the size and importance of the potential environmental impacts using the LCI results (ISO 14040, 2006). LCIA is a methodology used in analyzing the contributions of the resource extractions and wastes/emissions in an inventory to a number of potential impacts (Rebitzer et al., 2004). It is a tool that assists the analysts to unravel those releases (i.e. into air, water and land) and resource applications that are likely to contain the maximum potential to result in damage. In an LCA study, LCIA categorizes the individual releases (i.e. emissions to air, water and land) from the LCI stage to different impact categories, which jointly represent the LCIA profile for the product or building system.

According to ISO 14044 (2006), the LCIA consists of mandatory and optional elements (see Figure 2.5):

- Selection of impact categories, category indicators and characterization models;
- Assignment of LCI results to the selected impact categories (classification);
- Calculation of category indicator results (characterization).

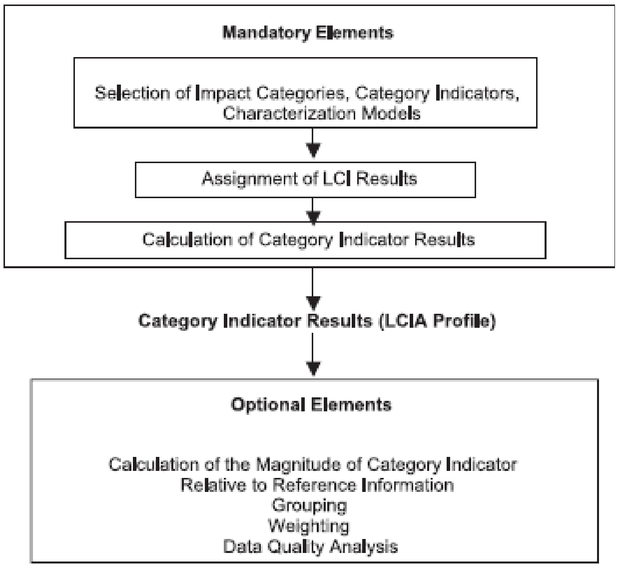

Figure 2.5: Elements of the LCIA phase (ISO 14040, 2006).

Selection of impact categories

In an LCA, the choice of impact categories must be consistent with the goal and scope (ISO, 14044, 2006), and reflect their significance to include: those in the literature; international agreements; the most significant environmental impacts attributed to the building sector; and regional and national policies. There are a few examples of studies that based the selection of environmental impact categories on some of the above factors. A Swedish study, Adalberth et al. (2001), using LCA evaluated four multi-family buildings and global warming as an environmental category was selected in response to a 1999 Swedish policy on environmental targets. Nemry et al. (2010) assessed options to reduce the environmental impacts of the residential buildings in the EU and selected environmental impacts categories based on scientific robustness, relevance and practicability. The main impact categories can be summarized as human health consequences and ecological consequences. Along this range, environmental impacts refer to (LBP & PE, 2007):

1. Global criteria including resource depletion; global warming potential (GWP); and ozone depletion potential (ODP).
2. Regional criteria such as acidification potential (AP) and land use.
3. Local criteria such as human and eco toxicity potential; eutrophication potential (EP); and photochemical oxidant creation potential.
4. Other criteria such as nuisance (noise, odour, landfill demand, and ionizing radiation).

Classification

Classification refers to the compilation, tabulation and grouping of linked resource uses and releases (emissions to air, water and soil) across all life cycle phases into impact categories. These emissions inventory data are in the form of the mass released into the environment e.g. 1 kg for every functional unit. One inventory item may have multiple properties and therefore would have multiple impacts. For example, ammonia is both a global warming agent and has the potential to create acidic precipitation or contribute to eutrophication which eventually may result in adverse effects on ecosystems, agriculture and ground water. Attention must be given by the analyst to naming rules or classification mismatches or omissions may occur (Bare and Gloria, 2005). For example, Dreyer et al, (2003), compared CML2001 and EDIP97 characterisation methods both of which belong to the same impact category approach, and found that, for nutrient enrichment (Eutrophication), the inclusion of non-contributing COD (i.e. inventory) in the CML2001 method resulted in higher impact score for CML2001. Figure 2.8 illustrates the principle of classification in LCA based on previous Japanese study,

Characterisation

Characterisation involves the calculation of category indicators results. Unlike impact categories, category indicators represent damage assessment, and refer to models associating emissions and resources used to end-point indicators. They are the quantified representation of the damage emanating from impact categories (see Figure 2.6 below).

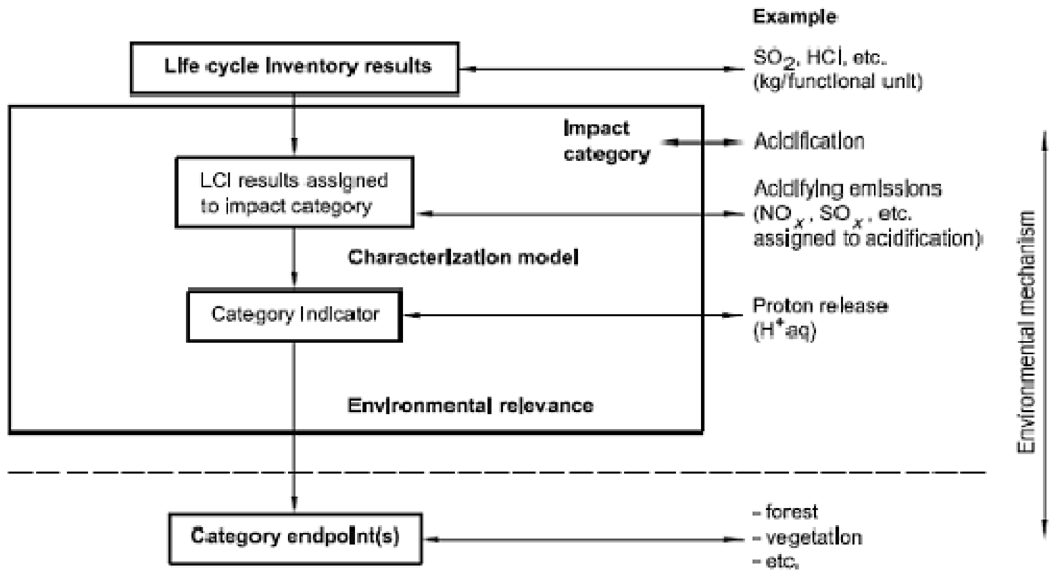

Figure 2.6: Concept of category indicators (ISO 14044, 2006)

Characterisation is the third of the three compulsory elements of a life cycle assessment (selection of impact categories, classification and characterisation). Characterization quantifies/estimates the amount of environmental impact resulting from the functional unit studied in the LCA. The real evaluation of impact entails multiplying each chemical (emissions in mass) by the corresponding characterisation factor (the effect per unit of emission), and summing the results within each impact category. Characterisation factors directly express the relationship between inventory data and impact category indicators. They are a gauge of potential harm by a chemical with an impact category

(Bare and Gloria, 2005), and are also available in the literature in the form of databases, as well as in LCA support tools (Pennington et al., 2004).

Using this approach (for each inventory item), an individual score can be evaluated for each applicable impact category. Equation 1 is then used to calculate impacts for individual inventory items (i.e. the relative contributions of the inventory items [chemicals] to a given impact category). The impact for the individual inventory items are thereafter aggregated for a given impact category with findings presented in corresponding units (i.e. through the use of a reference term for contrast), such as kg CO_2 equivalents for global warming or $KgSO_2$ equivalents for acidification potential.

$$M_a = \sum_a F_a * I_a \quad \text{(Equation 1)}$$

Where, M_a (kg) is the impact score for each inventory within each impact category (emissions in mass), a is the chemical (i.e. emissions into air, water and soil), F_a is the characterisation factor, and I_a is the emission inventory of chemical a (kg). Then, the sum of the impact for each impact category, *(i)* is obtained using equation 2 below:

$$P_i = \sum_a M_{i,a} \quad \text{(Equation 2)}$$

While the characterisation factor of global warming potential (GWP) of carbon dioxide is 1, the characterisation factor of GWP of nitrous oxide is 298. All of these suggest that one molecule of nitrous oxide is likely to impact on climate change with a potency of 298 times that of carbon dioxide. Furthermore, a GWP500 of 100 implies that 1 kg of the substance has the same cumulative climate change effect as 100 kg of carbon dioxide during a 500 year time period.

Optional elements of LCIA

In addition to the elements of LCIA listed in the previous sections, optional elements can be used depending on the goal and scope of the LCA (ISO 14044, 2006). These relate to normalisation, grouping, weighting and data quality.

Normalization of indicator results is aimed at a better understanding of the magnitude of indicator results relative to reference information. Normalisation allows equal representation of indicators when preparing for additional procedures, such as grouping, weighting or life cycle interpretation. It involves the calculation of relative contribution of the indicator with respect to a reference boundary, usually a region or country during a time period (e.g., 1 year) (Bare and Gloria, 2005). For example, results of GWP (all emissions) obtained for Germany are normalised (divided by the population) on a per capital basis.

Grouping is a qualitative or semi-quantitative process that involves sorting and/or ranking results across impact categories (Pennington et al, 2004). It involves assigning indicators to grade categories as defined in the goal and scope definition, and in a given hierarchy, e.g. high importance, medium importance, and low priority.

Weighting refers to a more formal procedure of grouping involved by the assignment of comparative values or weights to diverse indicators, permitting inclusion across all indicators. Numerical factors based on value choices are used to facilitate comparison across impact category indicators (or normalized results) and it is often applied in the form of a direct weighting factor (Pennington et al, 2004).

Life cycle interpretation

LCA interpretation is the phase in which the results from the inventory analysis and the impact assessment are considered together or, in the case of LCI studies, the results of the inventory analysis only (ISO 14044, 2006). The phase refers to the systematic reporting of the results of the life cycle analysis, using the most informative way possible and identifies the need and opportunities to reduce the impact of the building on the environment (UNEP/SETAC, 2006). The phase is also expected to deliver results that are consistent with the defined goal and scope and which reach conclusions clarify limitations and offer recommendations. Interpretation of a life cycle study is also the explanation, or analysis of the results of the inventory analysis and impact assessment phases based on the goals of the study (see Figure 2.7).

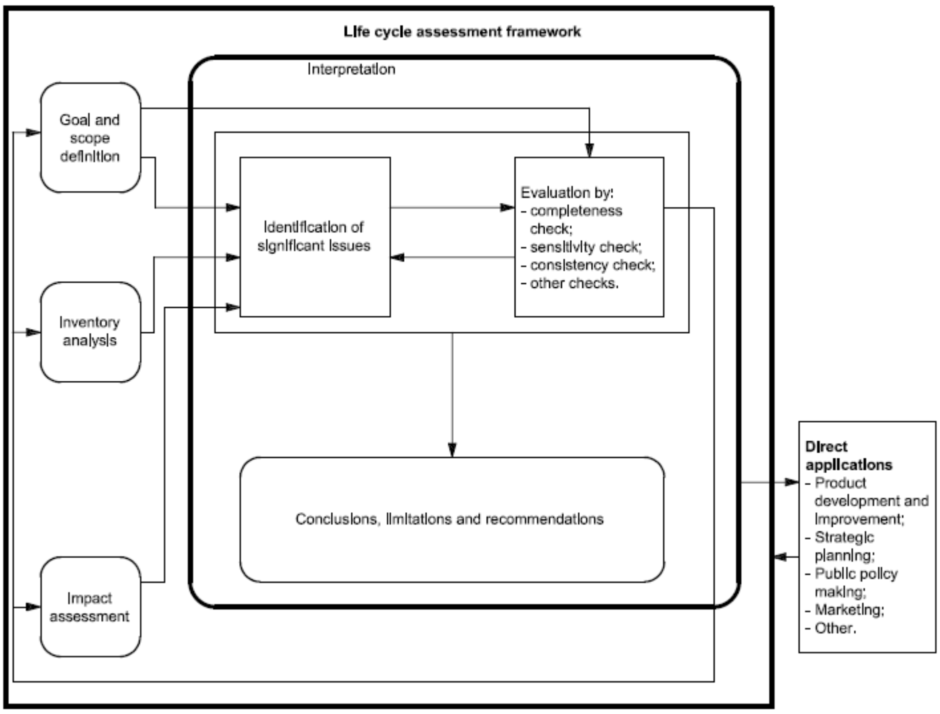

Figure 2.7: Relationships between elements within the interpretation phase with the other phases of LCA (ISO 14044, 2006)

There are three main techniques to perform an evaluation of the results of the inventory analysis and impact assessment phases (ISO 14044, 2006): completeness check; sensitivity check; and consistency check

The results of uncertainty analysis and data quality analysis are required to supplement the above checks. In an LCA study, a completeness check is aimed at ascertaining the availability of all relevant information and data required for the interpretation, as well as considering the need for missing information to satisfy the goal and scope of the LCA. Overall, the sensitivity analysis procedure involves a comparison of the results obtained using certain given assumptions, methods or data with the results obtained using altered assumptions, methods or data. Furthermore, sensitivity analysis involves checking the influence of varying assumptions and data by range (e.g. ± 25 %) on the results; both results are then compared. The results of the sensitivity analysis can then be expressed as the percentage of change or as the absolute deviation of the results, thereby allowing the identification of significant changes in the results (e.g. larger than 10 %). The aim of the consistency check is to establish whether the assumptions, methods and data are consistent with the goal and scope.

2.3.2 Process analysis

In this section process analysis as one the techniques of environmental accounting is discussed.

In an LCA study, process analysis trails flows of materials within the system boundary of the building system in order to determine the measure of primary energy needed to deliver a certain product or service. This is in contrast to input-out-put analysis where the flows are expressed in monetary terms. Traditionally, process analysis has been the method widely used to determine the primary energy and primary energy-related GHG emissions attributable to retrofitting buildings, and it is usually undertaken at an industrial level through the measurements of energy and material flows during production processes (Acquaye, 2010). As both LCA and process analysis are based on the same structure, they share a common framework based on ISO14040 and 14044. The flows of materials are in kilogrammes (kg) or tonnes (t) of materials. In the compilation of LCI, a process flow diagram is used to indicate how processes of a product system are interconnected through material flows (Suh and Huppes, 2005). For example, in the solid concrete floor system indicated in Figure 2.8, a unit of solid concrete floor upgrade is produced using 3,990kg of floor screed, 276.6kg of polyurethane rigid insulation foam, 24,273kg of ready-mix concrete, 474.5kg of floorboards and given GaBi software energy intensities for the range of process units, and it is used for the residual service life of the building. The results generated by the internal processors of the GaBi software tool for the above procedures are in the form of primary energy (MJ or kWh) and primary energy-related emissions (kg), and are referred to as life cycle inventory of the study based on process analysis. Other examples of the relevant unit processes of the study system are included in Appendix 1.

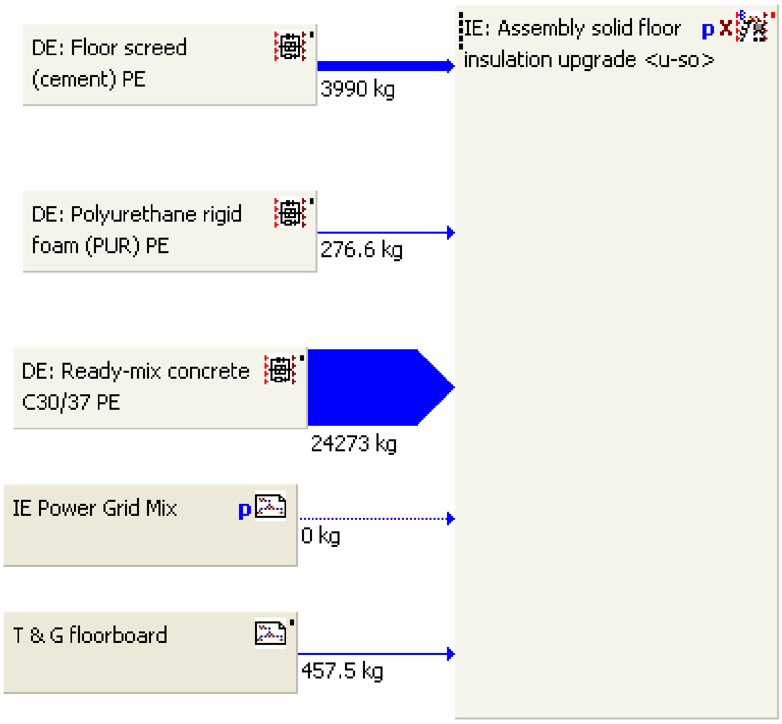

Figure 2.8 – Assembly of chain of processes and sub-plans to depict a stage (assembly of solid concrete floor upgrade) of the building system

The strengths of process analysis are its ability to provide more accurate and detailed process information with a relatively more recent data (Suh and Huppes, 2005). However, a major drawback of the process analysis technique is its incomplete system boundaries, as it is virtually not feasible to collect process-specific data for an economy, and the problem has led to the use of input-output analysis in LCA (Suh and Huppes, 2005). Sources of data for process-oriented analysis are mainly based on inventory databases.

A search through the literature indicates that international study contains only a few applications of the use of process analysis to compare environmental impacts for different buildings across life cycle phases. See examples of theses studies in Adalberth et al, (2001), Scheurer et al, (2003), Gustavsson and Joelsson (2010), Itard (2007), Blanchard and Reppe (1998) and Keoleian et al, (2001). The literature contains only one application of the use of process analysis to perform life cycle analysis of housing stocks. See an example of this study in Nemry et al, (2010), and this is performed at a regional level. A search through international literature did not reveal any applications of the use of process analysis to perform life cycle analysis of housing stocks at a national level.

2.3.3 Input-output analysis

Unlike process analysis, input-output analysis trails monetary flows in order to determine the measure of primary energy needed to deliver a certain product or service. The flows are expressed in monetary terms. The results of the input-output analysis are generally expressed as the energy intensity of the output of the sector. Wassily Leontief (1906-1999), who published US Tables for the years 1919 and 1929, developed economic input-output as an alternative to process modelling, the basis for I-O-LCA (inter alia). While input-output analysis is regarded as an alternative to process-oriented analysis, the product system of an input-output analysis comprises supply chains and is modelled using economic flow datasets in the form of Tables (Rebitzer, et al., 2004) and such data can be converted from monetary values to yield data on an energy basis (Hammond and Jones, 2008). The main source of these databases is through historical records which are mainly put together and supplied by statistical agencies of national governments. Then emissions and related impacts are assigned to various industrial sectors.

The strengths of the I-O-LCA is in its ability to reduce evaluation time for the analysts, a more complete system boundary within the national level compared to process analysis, especially as it usually reflects a wider range of sectors, together with balanced data on sectors not easily covered by process analysis. However, the major limitations of the I-O analysis are its lack of process specificity, together with risk of inaccurate results if national economy is mainly import oriented, and if economic flow databases (tables) are not regularly updated. Table 2.3 illustrates the main differences between the three techniques of environmental accounting.

Table 2.3: Principal differences between process-LCA and input – output (I-O) LCA

Process-oriented-LCA	Input/output-LCA	Hybrid-LCA
Relies mainly on unit process data	Relies on economic flow databases	Relies on full process analysis, and then uses I-O analysis only for cut-offs (i.e. to finish-up)
Commodity flow units are mainly physical units, such as mass of materials and energy fluxes	Commodity flow units are in terms of goods and services; and monetary flows	Combines commodity flows units of both process-LCA and I-O LCA
Operates on the basis of the level of unit processes	Operates on the basis of sector detail of goods and services	Functions on the basis of both the levels of unit processes and detail of goods and services
Incorporates complete life cycle	Does not always assure a total upstream system boundary (e.g. coal mining, etc), especially when the national economy-based I-O table relies mainly on imports	By combining the advantages of both process-LCA and I-O LCA, hybrid-LCA incorporates complete life cycle
Incomplete system boundaries	More complete system boundaries compared to process analysis	Increased complete system boundaries
Unit processes are precise and full	Lack process specificity	Preserves process specificity
Most excellent to evaluate or contrast precise options within a given sector	Offers balancing data on sectors not easily covered by process analysis	
		Risk of double counting
	Risk of inaccurate results if national economy is mainly import oriented	Risk of inaccurate results if national economy is mainly import oriented
	Risk of inaccurate results if economic flow databases (tables) are not regularly updated	Risk of inaccurate results if economic flow databases (tables) are not regularly updated

2.3.4 Hybrid analysis

A process analysis provides more accurate and detailed process information with relatively more recent data, while I-O analysis reduces evaluation time for the analysts, and with a more complete upstream system boundary within the national level compared to process analysis, especially as it usually reflects a wider range of sectors, together with balanced data on sectors not easily covered by process analysis. Both I-O analysis and process analysis can be combined to yield a third method known process-based hybrid analysis. Thus, a hybrid-process analysis can then be said to comprise mainly a process-analysis augmented with input-output analysis. A hybrid-LCA therefore, tends to overcome the main disadvantages of each method by combining the advantages of both methods. A hybrid-LCA can then be said to comprise mainly a process-LCA augmented with input-output-LCA. A hybrid analysis has been developed to overcome the main disadvantages between process and I/O analysis by combining the advantages of both methods (*inter alia* Morigushi et al. (1993) and Suh and Huppes, 2002).

The principal limitations of hybrid techniques are risk of double counting and extensive time requirements to produce results (Menzies et al. 2007). Other draw-backs of hybrid methods include risk of inaccurate results if economic flow databases (tables) are not regularly updated and the national economy is mainly import oriented. For example, increased proportion of imported components in the product system in question may result in wrong specification of imports which may well be more significant than that due to cut-off in process-based LCA (Suh and Huppes, 2005). However, a search through the literature did not reveal research studies focusing on hybrid models that combine the advantages of the process and input-output analyses to analyse impacts of dwellings at individual dwellings or stocks level across life cycle phases.

2.4 Environmental accounting software tools

There are two main categories of environmental accounting tools - interactive tools and passive tools. They assist in improving environmental performance of buildings by informing the decision-making process for users and stakeholders to unravel the effects of different building intervention options. Tables 2.4 and 2.5 illustrate the main similarities and differences between different energy tools and LCA tools, respectively.

Table 2.4: Indicative, non-exhaustive list of LCA software tools

LCA tools for buildings and building stocks	**Country code**	**Comment**
GaBi[a]	GER	Performs full life cycle analysis of buildings and building products, and enjoys wide coverage across many regions due to their extensive background datasets; supports parameterized modelling as well as scenario analysis
SimaPro[a]	NL	Also performs full life cycle analysis of buildings and building products, and enjoys wide coverage across many regions due to their extensive;
TEAM[a]	FR	Energy switch might be a problem for users within the UK-Ireland axis (France is main 'nuclear' fuel specific)
LCAiT[a]	SE	
SBI's LCA tool[a]	DK	Contains a database and an inventory tool, and has a method to handle uncertainty, but it requires further research into weighting.
EQUER tool[a]	FR	It has an advantage of a direct link to an energy simulation tool; Improvement of the tool is required regarding concerns over the accuracy of the data bases and the actualisation of environmental indicators
Envest 2 estimator[b]	UK	UK specific and consists of 13 environmental impacts as Ecopoints score
ATHENA[b]	CA	
LISA[b]	AU	LCA decision support tool (table and graphical form).
Boustead[a]	UK	contains nearly 13 000 individual unit operations
Umberto[a]	DE	Its suitability within the UK – Ireland axis could not ascertained
BREEAM[c]	UK	
LEED[c]	USA	
SEDA[c]		
BEE 1.0[a]	FI	Input and output table in Finish- language may be a problem. It has no means of optimising designs
Eco-Quantum Research[a]	NL	It is time consuming tool; Further research into the following is required for tool quality assurance: data infrastructure, system boundaries, data allocation and weighting factors

[a]Product comparison; [b]Whole building decision support tools; [c]Whole building frame work assessment

2.4.1 Interactive software tools:

Interactive software refers to LCA tools for buildings and building stocks, and energy and ventilation modelling software (IEA 2001). While energy modelling software tools measure or calculate operational energy ratings of a dwelling, most LCA models go a step further by performing these functions across different life cycle phases.

LCA tools for buildings and building products: LCA tools for buildings and building products are used for assessing the links between building specifications and potential environmental impacts as they interpret aim and management options into purposeful declarations about environmental effects and impacts (IEA, 2008).

An LCA tool assembled for modelling and assessing a given building system must have access to a database that provides adequate LCI and LCIA background datasets for the building system and processes.

LCA software tools can be broadly divided into three categories (Ortiz, 2009): whole building frame work assessment (e.g. BREEAM [UK]) and LEED [US]); whole building decision support tools (e.g. Envest [UK], ATHENA [Canada] and BEES [US]); and product comparison tools (e.g. SimaPro [Netherlands], GaBi [Germany] and TEAM [France]). The principal difference between these tools is their levels of background datasets and sources of data which in turn influence their levels of coverage. For example, Scheuer et al. (2003) argued that due to data limitations, together with the large range of construction techniques and materials choices, Athena, BEES and Envest were incapable of modelling the entire building. Furthermore, while the Envest Ecopoints is UK specific and consists of 13 environmental impacts as Ecopoints score, SimaPro and GaBi contain extensive background datasets giving extensive coverage of impacts across different countries and regions, together with the effect of rich data, availability of a robust internal processor, ability to support parameterized modelling as well as scenario analysis, all of which make analysis less cumbersome and reduce time. On the basis of the above, it is most unlikely that LCA tools that do not meet the above criteria would be preferred.

Several LCA tools had been used to assess buildings. See examples of these in Nemry et al. (2010), Itard (2007), Scheuer et al. (2006) and Gustavsson and Joelsson (2010).

Choice of LCA tool

Having met the criteria discussed in the above review of literature, GaBi 4.4 software is a good choice for use in the evaluation of the environmental impacts attributable to the representative archetypes in this thesis. The following paragraphs discuss the attributes, databases and application of the GaBi 4.4 software.

On the basis of the conclusion from the literature review that was performed in Chapter 2, GaBi 4.4 LCA software tool was selected to evaluate the environmental impacts due to energy use of the representative archetype dwellings, based on its clear benefits over the other LCA software. These benefits include extensive background datasets giving extensive coverage of impacts across different countries and regions, together with the effect of rich data, availability of a robust internal processor, ability to support parameterized modelling as well as scenario analysis, all of which make analysis less cumbersome including reduced time. In this section, a summary of the GaBi software data, main assumptions and application are discussed.

GaBi 4.4 is an LCA software tool developed by the PE International of Germany (LBP & PE, 2007). It is designed to be flexible to assist in policy making and comprises a database and an inventory tool. The GaBi 4.4 database represents standard databases used in industry, additional databases of ELCD, Plastics Europe, and extension databases as complimentary. GaBi 4.4 contains construction database or datasets which encompass the mainly relevant construction materials, including additional specialised materials used in the construction of buildings. The construction database is categorised into mineral products (including concrete, concrete products, bricks and natural stones); ready-to-use building materials (including different types of windows and frame types).

The technologies of the transportation datasets are representative Europe wide. These technologies can be adapted in different countries to suit country specific background datasets (e.g. transportation distance and weight of materials to be transported).

GaBi 4 validation

An attempt was made to validate GaBi 4.4 software. While a search through the literature did not reveal any LCA studies that have been carried out on housing stock at a national level using either GaBi 4.4 or similar LCA software (i.e. with similar characteristics), there are studies indicating the validation of GaBi 4 based on the results of their energy and emissions analysis. In an attempt to update the steel industry's worldwide LCI database and improve the rigorous LCI methodology for steel products in accordance with ISO14040:20061 and 14044:20062, the World Steel Association (WSA 2011) performed LCI study of some of steel products. Using a previous data collection studies which was based on TEAM LCA software, the world steel LCI model was created in GaBi 4 in a new review process of the second update of the first LCIs provided in 1996/96. The results indicate that the defined and achieved scope of the LCI study was found to be consistent with the stated goals of the study. Stokes and Horvath (2009) evaluated the energy and emission impacts of supplying water using GaBi 4 in a hybrid life cycle analysis, the results indicate that the California analysis and Dubai (United Arab Emirates) analysis show realistic energy use and air emissions impacts. Similarly, GaBi 4 software tool has been used to determine the environment impact of the EU residential buildings. See the details of this study in Nemry et al, (2010).

Application of GaBi 4.4

Within the database, all computable input i.e. from 'Background data' as earlier discussed in the preceding section (materials, products and energy fluxes) and output (emissions) are stored for each of the processes. The GaBi database (background datasets) and inventory tool are then used to perform LCAs for building elements or building materials. In this way, it is possible to analyse individual parts of a building system or product in more detail. For example, in an LCA of a building retrofit project, it is possible to evaluate the environmental impact contribution of wall dry-lining, floor insulation improvement, roof insulation and even impacts associated with retrofitting renewable technologies to the building. Similarly, in this way, it is possible to establish which of these processes contributes most to the total environmental impacts of the building.

In carrying out an LCA the inventory tool calculates the overall inputs and outputs which occur during the lifetime of the building using the entry of LCI input flows (i.e. life cycle inventories of the various processes). Inputs represent resource uses over the lifetime of the building, and outputs are energy used and emissions.

However, in cases when a particular background dataset was not available, additional background datasets can be modelled, using direct manufacturers' data and based on the same boundary conditions, including the use of the equivalent modelling method. These data can be obtained from manufacturers' brochures, as well as through personal contacts (see Table 4.4 for sources of additional data). One of such example is the International Iron and Steel Institute (IISI) which supplied life cycle inventory data for the steel products used in the study. These products include finished cold rolled coil (used in the manufacture of domestic appliances) and hot dip galvanized steel (used both in domestic appliances and in heating and ventilation systems). The background datasets can then be validated through completeness checks, sensitivity checks and consistency checks. Completeness checks refer to the procedure of confirming that the assumptions, methods and data are reliably applied throughout the study and in accordance with the goal and scope definition. Sensitivity checks involve verifying that the information obtained from a parameter variation analysis is relevant for making the conclusions and recommendations. Consistency checks aim at ensuring that all relevant information and data required for the interpretation are available and complete.

Energy software tools

Energy software tools refer to tools used for calculating operational phase energy rating of a dwelling. Overall, there are several examples of energy software tools - DEAP model developed by the Irish government, HOT 2000 series (CANADA), ESP-r (UK), EnergyPlus software (US Department of Energy); EDEM/HEM (UK), BEAM model of Ecofys, INSTRUM-R simulation tool and Canadian Residential End-use Energy Model (CREEME) developed by the Canadian Residential End-use Energy Model and Analysis Centre. In contrast to LCA tools, energy software tools focus on the operating phase of a building only, and the results do not explore the potential environmental impacts at local, regional or global levels.

Energy software tools are particularly useful as they feed house annual operation energy into LCA software tools. Depending on the algorithms of the LCA tool, input for the annual purchased heat energy (PHE) as outputs from an energy modelling tool can be fed into an LCA tool either in kWh/yr or kg/yr. For example, GaBi 4.4 belongs to the group of LCA tools where inputs for house annual PHE from an energy modelling tool can be fed in kg/yr or kWh/yr.

There are three main categories of energy modelling tools. These include asset rating tools, whole building energy simulation tools and those tools that combine the functions of asset rating with energy improvement options. An example of asset rating tools that mainly perform the function of building regulations compliance is the Irish Dwelling Energy Assessment Procedure (DEAP). Similarly, an example of those tools that combine the functions of asset rating with energy improvement options is the UK ESRU Domestic Energy Model/House Energy Model (EDEM/HEM). In contrast to asset rating and those tools that combine the functions of asset rating with energy improvement options, the use of energy simulation tools to develop typical whole building models is time consuming and cumbersome (Hand et al, 2005). Depending on the type of conceptual outlooks, simulation tools are still difficult to use by users (Clarke et al 2004). A typical example of energy simulation tools is the UK ESP-r.

Table 2.5: Indicative, non-exhaustive list of energy modelling software tools

	Energy and ventilation Modelling software	**Country code**	**Comment**
1	BEAM model by Ecofys	DE	Restricted only to the use of heating energy and the related CO_2
2	EnergyPlus, DOE 2	USA	Whole building energy simulation tool
3	EPIQR	CH	Contains details for all climatic regions in the EU-25 (Nemry et al., 2010); tool for surveyors, architects or building owners to select options for upgrades (Caccavelli and Genre, 2000). Combines energy evaluation with improvement options; local adaptation may be a problem
4	HOT 2000	CA	In addition to evaluating operation energy, also calculates embodied energy and other environmental impacts.
5	EDEM/HEM	UK	Combine energy evaluation with improvement options; can easily be adapted using local weather data; local adaptation may be easy; representative of region
6	ESP-r	UK	Appears very efficacious but still requires further improvement to make it more users friendly.
7	BREDEM	UK	local adaptation may be a problem
8	DEAP	IE	Asset rating; mainly for building regulations compliance; assumes household standard use of energy; does not support settings of some context parameters
9	Energy 10	USA	Switching energy mixes could be a problem
10	eQuest, a DOE 2 interface	USA	Local adaptation may be difficult.
11	EQUA ENORM tool	SE	Energy simulation; local adaptation may be difficult.
12	BEAM, developed by ecofys	DE	It use is restricted to the use of heating energy and related CO_2 emissions
13	BRI LCA TOOL	JP	Adaptability to the UK – Ireland axis and switching energy mixes could be a problem.
14	Power DOE	US	Switching energy mixes could be a problem.
15	HTB-2	UK	Dynamic thermal simulation; model was intended as a general-purpose finite difference simulation code for energy and environmental performance of buildings (Lewis & Alexander, 1990).

The main sources of data for both asset rating tools and those energy tools that combine the functions of asset rating with energy improvement options include the descriptions of each individual dwelling of the stock of housing by its geometric details, thermal characteristics and operating parameters. On the other hand, the main sources of data for energy simulation tools for dwellings include weather (including air temperature, humidity, solar radiation, wind speed and wind direction), occupants and occupants behaviour, and appliances (including heating systems and water storage tank) (See Hansen and Lambert 2011).

For energy modelling software, in all cases they appear to be capable of performing the function of evaluating the operational energy of the buildings. However, for those tools that combine the functions of asset rating with energy improvement options, adaptation to suit regional condition and a lack of the demand-related inputs (context parameters) are likely to be a problem. It should be noted that the inclusion of the relevant profiles of demand-related inputs on the interface of these tools allows a user to establish the magnitudes of energy and CO_2 to be quantified. These demand-related inputs include 'grid CO_2 intensity' (indicating a reduced/increased CO_2 emissions factors for the electricity grid); 'appliance' (i.e. illustrating a profile of reduced/increased use of appliances by occupants); 'heating demand' (i.e. indicating options of a reduced/increased profile of heating demand by occupants); and 'hot water demand' (i.e. gives a reduced/increased hot water heating profile). For example, the EDEM/HEM energy modelling software has the above criterion whereas similar regional software, DEAP does not. In addition, representativeness of region as one of the criteria for selection of energy software is considered important especially as the range of most LCA tools currently available contain regional/European datasets. On the basis of the above, it is most unlikely that energy modelling software tools that do not meet the above criteria would be preferred.

The use of energy modelling software for different upgrade strategies is well established and can be found in several previous studies - see examples of studies in- Clarke et al, (2008), Farahbakhsh et al., (1998), Griffith and Crawley, (2006), Palmer et al., (2006), Petersdorff, et al., (2006), Jaccard and Baille, (1996), and Huang and Broderick (2000).

Choice of energy modelling tool

Having met the criteria discussed in the above review of literature, EDEM/HEM energy software is a good choice for use in the evaluation of the annual house energy in this thesis. The following paragraphs discuss the attributes and application of the EDEM/HEM software.

EDEM/HEM is a Web-based housing energy tool developed on detailed simulation models aligned with national housing survey data (Clarke et al, 2008). EDEM/HEM can assess energy and carbon-dioxide (CO_2) emissions at any scale at individual, local, regional and national levels. It addresses the challenges perceived in existing static models such as limited ability to represent dynamic behaviour and the use of only a small number of representative designs to perform detailed simulation. It is designed in response to demand from policy makers to assist in evaluation of retrofit scenarios for emissions abatement across a range of potential future low emissions solutions, behaviours and environmental factors. The tool can also assist in scenario cost evaluations.

In order to meet the requirements of the EU Energy Performance of Building Directive (EPBD), EDEM/HEM was used on half of the Scottish Building Standards Agency and South Ayrshire Council to assess the impacts of energy efficiency improvements including new and renewable energy technologies. The results of the above project indicate that the EDEM/HEM predictions were in agreement with the UK Government's SAP (Simplified domestic sector method) (ESRU, 2008). EDEM/HEM was applied at the command of the UK Building Research Establishment to undertake an evaluation of the impacts of controls on energy and carbon performance for a range of dwelling types, heating and hot water system types and control scenarios (ESRU, 2008). Overall, the methodology of the EDEM/HEM software is structured to ease project development and application to other countries with significantly different building stock and climate.

EDEM/HEM relies on background survey data permitting a breakdown of the housing stock into characteristics parameters which can be utilised to assess energy and carbon performance (Clarke et al, 2008), it would be recalled that in this study the background survey data is Energy Performance Survey of Irish Housing (EPSIH, 2005).

Application of EDEM/HEM

An application of EDEM/HEM in an evaluation of any given upgrade in a study e.g. for Ireland is performed as follows: First, the demand-related inputs for the analysis is set regarding climate, heating demand, hot water demand, appliances grid CO_2 intensity, etc). Second, the performance of the Base-Case representative archetype dwelling i.e. “As Is” is predicted by entering its input data for fabric and heating system determinants. This assigns the dwelling to an appropriate thermodynamic class (TC), and the level of performance is set as the ‘Base’ for comparison. Third, the new changes in input data for fabric and system for a given retrofit scenario are applied (which moves the ‘Base’ to a different TC), while the predictions of energy for the option is then simply ‘read off’. Next, this procedure is repeated for each of the representative archetype ‘Base-Case’ dwellings, across the differing retrofit scenarios. Thus, for each archetype ‘Base-Case’ and its corresponding retrofit scenario, energy predictions as output from the HEM software are recorded. Depending on the algorithms of the LCA software, the annual purchased heat energy (PHE) results (kWh/m^2.yr) of EDEM/HEM software is either fed as kWh/yr or kg/yr (See previous discussion on this in the preceding paragraphs of this section). For electricity usage, the results of EDEM/HEM are fed as kWh/yr.

2.4.2 Passive tools

Passive tools are non-LCA/energy tools. Unlike LCA and energy tools discussed above, the contribution of information of passive tools to environmental assessment tends to be inactive as they do not perform evaluations or change design (IEA 2008). They contribute complementary static information to the LCA process, and are therefore complementary in their role. Passive tools are used in environmental assessment frameworks and rating systems; environmental guidelines or checklists for design and management of buildings environmental product declarations, catalogues, reference information, certifications and labels.

There are several examples of passive tools (IEA, 1998). These include: laws, guidelines, check-lists, case studies of best practices, product labelling (ecological and quality grading), product descriptions and recommendations.

2.5 Project evaluation measures

This section discusses life cycle cost analysis (LCCA) as an economic method of project evaluation including the various evaluation measures available to provide information on costs of building project alternatives. LCCA is used to calculate the life cycle costs (LCC) of a building system or combination of interdependent systems. LCCA is an economic method of project evaluation in which all costs arising from owning, operation, maintaining, and finally disposing of a project are considered to be possibly significant to that decision (Fuller and Petersen 1996). LCCA can be applied to any capital investment decision in which higher initial costs are exchanged for reduced future cost obligations. This suggests that LCCA can be applied to energy efficiency upgrade projects to determine potential cost reductions relative to a basecase. Overall, there are several project evaluation measures which can be used for evaluating the costs of building project alternatives. These include (LCC) and the supplementary LCC measures.

The LCC method of economic analysis is the basic building block of LCCA (Fuller and Petersen 1996). LCC is the overall cost of owning, maintaining, and disposing of the building system (s) over its service life, with all costs discounted to reflect the time value of money. The main attribute of the LCC method is that it can be used to choose two or more mutually exclusive alternatives on the cost of lowest LCC. The (LCC) method is extensively used for the economic analysis of investment projects over a service life. For example, the EU Commission Services initiated the examination of the issue of life cycle costing in the field of Green Public Procurement (GPP) since 2008 (EU Commission 2012). The initiative aims to lead to both cost and emission savings over the whole life cycle of purchased goods throughout the EU. The main attribute of the LCC method is that it can be used to choose two or more mutually exclusive alternatives on the cost of lowest LCC.

The supplementary measures of LCC include Net savings (NS), Savings-to-Investment Ratio (SIR), Adjusted Internal Rate of Return (AIRR), Discounted Payback (DBP) and Simple Payback (SPB). For a project alternatives, the NS is evaluated as the difference between the LCC alternative and the BaseCase LCC (Fuller and Petersen 1996). Overall NS is calculated using individual cost differences. Specific characteristics of the NS include its usefulness to evaluate economic performance of investments which reduce operational costs; the need for its calculation with respect to a given BaseCase; and a positive NS indicates a cost effective investment.

The SIR is used to evaluate the economic performance of a project alternative that indicates between its savings and its increased investment cost based on the NS (i.e. with respect to present value terms) (Fuller and Petersen 1996). The SIR can only be measured with respect to a given BaseCase. The main usefulness of the SIR is in its ability to rank that project along other independent projects as a guide for assigning limited investment funding.

Similar to the NS and the SIR, the AIRR is a relative measure of cost effectiveness. The AIRR can also be used as the same applications as the SIR; it can be used to accept or reject a single project relative to a given BaseCase. Overall, AIRR evaluates economic performance as an annual rate of return on investment (Fuller and Petersen 1996).

Discounted Payback (DBP) is one of the two payback measures that are frequently used for the economic analysis of a capital investment (Fuller and Petersen 1996). The time required to recover initial investment costs is evaluated using the DBP. It is a measure that can only be evaluated relative to a given BaseCase. Unlike the SPB, DPB is a preferred measure of computing the payback period for a project due to the requirement that cash flows occurring each year be discounted to present value prior to accumulating them as savings and costs.

Like the DPB, the Simple Payback (SPB) is also a payback measure that is frequently used for the economic analysis of a capital investment. However, SPB is more frequently used than the DBP and does not use discounted cash flows in the payback evaluation. During the payback period, the SPB in most realistic applications disregards any variations in prices e.g. energy price escalation. It should be noted that both DPB and SPB disregard all costs and savings, as well as any residual value, occurring after the payback date. These two payback measures cannot be used to rank independent projects for funding allocation. Overall, payback is best used as a screening measure for classifying single project alternatives that are distinctly economical that the time and outlay of a complete life cycle cost analysis (LCCA) is not needed. Overall, both SPB and DPB are used to evaluate how long it takes to recover investment costs (Fuller and Petersen 1996).

The previous paragraphs have shown that there are various evaluation measures available for estimating costs of building project alternatives over their service life. In this study, LCC as a method of economic analysis is considered most appropriate as it evaluates the overall cost of operating, retrofitting, maintaining, and disposing of the building system over its service life, with all costs discounted to reflect the time value of money.

2.5.1 Life cycle cost analysis

In the previous paragraph the conclusion was that the LCC method of economic analysis should be used in this study. This section discusses this method as a basic block of LCCA.

In a building project, life cycle cost analysis (LCCA) estimates costs over the service life of a product or service. LCCA is used to estimate the total costs of building project alternatives and to select the option that provides the lowest total cost of ownership consistent with its quality and function (Fuller 2007). However, the lowest LCC project alternative may not always provide this quality and function. For example, in building project alternatives an increased LCC but accompanied by reduced emissions for the passive house standard scenario should not suggest discarding the option for the BaseCase house scenario with increased emissions but at a lower LCC. What should be essential is the fulfillment of the application being considered even if it does not represent the lowest life cycle cost.

LCCA can be used to perform both discounted net present value (NPV) or non-discounted NPV. The present value (PV) of a building alternative is the cash amount received or paid at a future point in time calculated using a discount rate. Thus, the NPV of a building alternative is the summation of all PVs.

In an LCCA all costs are recorded as base-year amounts in today's Euros: the LCCA technique escalates all amounts to their future year of occurrence and discounts them back to the base data to convert them to net present values (NPV). As the project-related costs which occur at various points in time over a service life cannot be directly merged since the Euro expended at various times are likely to differing values to the investor, these costs should first be discounted to their present-value equivalent amounts (Fuller and Petersen 1996). Similarly, in an economy under inflation, procuring ability of money wears away over time. Consequently, an investor will want a payment or additional revenue for deferring to the future the expending that Euro as well as demands more than a Euro at some future time to get corresponding procuring ability to a Euro held today. The cost of a particular commodity (e.g. energy costs) as of the base date must be adjusted to reflect the actual cost as of some future date using the nominal price escalation rate. Thereafter, the costs are added to achieve a consequential LCC that can be compared with the LCC of other alternatives.

2.5.2 Marginal abatement cost (MAC)

In this section marginal abatement cost (MAC) as another measure of evaluation is discussed. MAC refers to the estimation of CO_2 emissions reductions available in a given housing stock at a given cost of abating GHG emissions. MAC relies on LCCA. The technique is consistent with the ability to give insights into opportunities to cost of abating GHG emissions in project alternatives once the life cycle costs of the building alternatives and their total emissions for the period of study are known. The marginal cost of an energy project is the change in total cost that arises when the quantity of energy produced changes by one unit (Ayompe, 2011). Costs refer to additional investment costs relative to the no-intervention default option and may also include fuel cost savings and additional costs or benefits. A positive cost means there is a cost associated with reducing emissions, a negative value represents a saving.

GHG abatement is a major criterion for evaluating cost of abating GHG emissions of investment in new technologies. Abatement cost estimates represent a useful tool for policymakers and their advisors to evaluate the feasibility of achieving national or regional climate policy objectives (Motherway and Walker, 2009).

2.6 Service lives complete buildings

In order to evaluate the life cycle impacts of a building, its service life must be known. The value of service life of a building varies across author and study for various reasons, ranging from differing economic life times of buildings in the country in question to non-technical (e.g. rebound effect) and technical (e.g. durability of material). A commonly assumed service life of buildings is a 50-year period (Sartori and Hastnes, 2007). In some cases, the service life is chosen as a 40-year period (Blengini, 2009). Using both non-technical decisions and technical state of the buildings, Nemry et al, (2010) evaluated emissions reduction potential in EU buildings and explored the potential for a residual service live of 40 years for new dwellings and 20 years for older dwellings. Adalberth et al, (2001) assumed a service life of 50 years for four multi-family buildings in Sweden because the economic life span of a building in Sweden is about 40-50 years. Scheuer et al, (2003) explored a 75 year service life for a mixed use building in Michigan. 50 years for retrofit was assumed in this study.

2.7 Overview of the EPSIH housing database

The housing database used in the thesis is the Energy Performance Survey of Irish Housing (2005 EPSIH). In this section an overview is provided of the housing database. The following provide information of the procedure used in undertaken the surveys.

In 2005, a survey of energy use in a sample of Irish houses entitled 'Energy Performance Survey of Irish Housing' was undertaken to determine the actual energy consumption compared with the theoretical energy consumption of a sample of Irish dwellings and to determine the levels of compliance with current and previous Irish regulations governing the energy performance of Irish dwellings from 1997 onwards. Furthermore, the study aimed to demonstrate an economical method of conducting building energy rating surveys in the context of the implementation of the EU Energy Performance of Buildings Directive in Ireland.

The sample size was 150 dwellings, representing 25 of the 26 in the counties of the Republic of Ireland. The housing sample profile was based on the true geographical distribution of the three dominant energy related characteristics: (a) age of dwelling, (b) type of built form and (c) tenure of occupancy – in that order of importance. The survey sample mix was defined from national and regional statistical data through a statistical analysis, with final additions to take into account a number of specific secondary local housing characteristics.

The data was collected between January and March 2005 by surveyors who visited each dwelling. All dimensions were measured. A log of occupancy was kept by household members. Air infiltration was measured using 'blower-door' technology. Boiler efficiency was measured based on flue gas measurements under full load conditions. Heating system controls were recorded on site. A log of age of building and tenure was kept by Sustainable Energy Ireland (SEI) and Local Government Authorities. Wall and roof insulation type and thickness were measured accurately in the majority of dwellings, through unsealed openings for plumbing and electrical services, the level of thermal bridging was measured using Infra red thermography. However, it was not feasible to establish the level of floor insulation through a non-invasive survey, as it was not realistic for the assessors to open up the floor to confirm the type of installation. In cases where it was not practicable to evaluate the ground floor, a 0.45 W/m^2K U- value was assumed for dwellings built after 1991, as required under both the 1991 and 1997 Technical Guidance Document (TGD), Part L. The Technical Guidance Document (TGD), Part L is a guidance document which applies to both new and existing dwellings regarding conservation of Fuel and Energy. In the absence of data, the assumption for the floors of buildings built earlier was that they generally had no floor insulation.

Heat Energy Rating (HER) methodology, as defined in the Irish Building Regulations TGD (2002), Part L (DEHLG, 2002) was used to evaluate the theoretical design energy demand of the building for space heating and domestic hot water. The Heat Energy Rating (HER) of a dwelling is a calculation of the annual energy output from the heating appliances (such as boilers, fires and electrical heaters) that provide space heating and domestic hot water (DHW) under standardised conditions of operation, room temperature and hot water use. The calculation software in Microsoft EXCEL format is an adaptation of the HER standard calculation worksheet provided in TGD (2002) Part L, Appendix C (DEHLG, 2002), with additional bespoke sheets for data on metered energy input, fuel type, heating system efficiency and occupancy.

The total energy use was obtained from historical electricity and fuel records over the period 2003-2004. When compared on average across all sample, the theoretical heat energy consumption was found to be 3.5% lower than the actual heat energy consumption, which provides good reliability to the theoretical model used in the survey, when applied to the Irish housing stock profile. However, the findings of the survey did not include the magnitude of the variability for the individual houses. The study uses this housing database as the principle source of energy use data, geometric details, thermal characteristic and operating parameters.

Irish Housing Survey of Housing Quality (INSHQ) database

The INSHQ contains detailed information from a representative sample of over 40,000 householders on building characteristics and building condition. Whilst survey interviews employed in this report present advantages in terms of wider population coverage, it lacks detailed information on many technical and structural features, and in particular those that are not easily accessible or visible (INSHQ, 2001-2002). These include detailed information on the depth of wall insulation, roof insulation between rafters, pipe-work insulation, insulation type/thickness to hot water storage tank, heating systems primary circuit, heating system control (for example some households find it difficult to understand heating system controls). It is also assumed that respondents gave inaccurate or inconsistent answers (INSHQ, 201-2002), partly a result of misinterpretation of the listed items in the survey questionnaire. Overall, the database represents only a ‘high level’ snapshot of housing quality at a national level.

2.8 Identification and ranking of key variables from scientific studies

To allow the ranking and selection of household variables in Step 3 of archetype development under methodology, 17 scientific studies on house energy efficient improvements were also reviewed. These studies contain results of household key variables of energy use, and were performed at a local, national or regional level - see examples of these studies in Lechtenböhmer and Schüring (2010), Firth et al. (2009), Clinch and Healy (199), Gustavsson and Joelsson (2010), Nemry et al. (2010), Oreszczyn et al. (2006), Hens et al (2001), Balaras et al (2007), Tommerup, Svendsen (2006), Reeves, (2010), Wall2006, Shanks (2006), Petersdorff (2006), Gustavsson et al. (2010), Clarke (2008), Gustafsson (2000) and Andrade (2001). Table 2.6 below shows the overall conclusion from the review of literature on variables influencing household energy use as indicated in 17 scientific studies on house upgrades.

Table 2.6: Ranking of variables of energy use as observed in scientific studies

Reference	**Study**	**Region/country code**	**Wall (U-value)**	**Roof (U-value)**	**Ground f floor U-value)**	**High performance window (U-value)**	**Air change rate (ac/h)**	**Internal temperature (°C)**	**Window size (m^2)**	**Wall to floor area ratio**	**Heating system efficiency (%)**	**Primary fuel type**	**Heat source**	**Floor area (m^2)**	**Number of occupants**	**DHW cylinder insulation type (mm)**	**DHW cylinder size (litre)**	**Pipe-work insulation (mm)**	**Dwelling type**
1	Lechtenbohmer, Schüring (2010)	**EU***	1	1	1	1													
2	Firth et al. (2009)	**UK**	2	2	2	2	2				1	1	1	2		1			2
3	Clinch and Healy (1999)	**IE**	4	2				3	5		1					6			
4	Gustavsson, Joelsson (2010)	**SE**	2	2	2	2	2				1	1	1						
5	Nemry et al. (2010)	**EU-27**	2	1		2	3												1
6	Oreszczyn et al. (2006)	**UK**	1	1	1	1					2								
7	Hens et al (2001)	**BE**		1	2	3					4								
8	Balaras et al (2007)	**EL**	1			3	2												
9	Tommerup, Svendsen (2006)	**DK**	1	1	1	1	2				4							3	1
10	Reeves (2010)	**UK**	1																
11	Wall (2006)	**SE**				3	1	5			2				4	7	6		
12	Shanks (2006)	**UK**	8	3	2	5	1												
13	Petersdorff (2006)	**EU-15**	1	1	1														
14	Gustavsson et al. (2010)	**SE**										2	1						
15	Clarke (2008)	**UK**	1	1	1	1	2		3	5									4
16	Gustavsson (2000)	**SE**	1	1	1	1	2												
17	Andrade (2001)	**PT**						1							2				

*Housing stock of the EU-27, Norway, Iceland, Croatia, and Leichtenstein.

2.9 Conclusions for Chapter 2

A number of information has been observed regarding the relevance of literature review to this thesis. This section attempts to link the information to the respective areas of the research carried out in the study. The key conclusions from the chapter are:

- Models which fully evaluate the life cycle energy and greenhouse gas emissions of national housing stocks to include the contribution of fuel supply chains to energy and emissions processes (such as exploration, extraction, refining, and transport) and services (such as the installation of materials and fit-outs including the servicing of heating appliances, are not reported in literature.

- The use of European datasets as background data as evident in the work of Nemry et al (2010) was identified to be appropriate for use in this thesis in the evaluation of embodied energy and emissions. However, but in this study the results of the operational impacts based on European datasets need to be presented along international and national sources of energy/emissions. In this way it is possible to identify the proportion of operational energy/emissions attributable to national sources for the purposes of making policy recommendations.
- This study proposes that the formation of archetypes should be based on the full set of key variables impacting energy use in Irish housing and the modes of their distribution. The main limitation identified in most of the reviewed literature is the use of weighted average value approach which this study considers not fully representative of the centre of the distribution of the key variables.
- The most commonly used functional unit in LCA is the 1 m^2 heated floor area and it is considered appropriate for use in this thesis.
- In most studies found in literature, environmental impact categories to be evaluated are selected based on regional and national polices, and this has been found appropriate in this thesis. Moreover, most environment indicators published by Irish government agencies focus on greenhouse gas emissions and primary energy.
- LCA is carried out based on two main categories of tools – LCA tools for buildings and building products, and energy software tools. At the level of housing stock, LCA tools that are appropriate for use should have extensive background datasets, a

robust internal processor and ability to support parameterized modelling as well as scenario analysis.

- GaBi 4.4 LCA software was found to be within this description and is preferred for use in the thesis to evaluate life cycle impacts.
- Similarly, 3 distinct categories of energy tools – Asset rating tools, those energy tools that combine the functions of asset rating with energy efficiency improvements, and whole house energy simulation tools. Those energy tools that combine the functions of asset rating with energy efficiency improvements were considered appropriate for this study, due to the level of available. EDEM/HEM energy modelling software lies within the above description.
- Life cycle cost analysis (LCCA) and Marginal Abatement Cost (MAC) represent the cost evaluation techniques considered appropriate for this study.
- 50 years is the commonly used service life of buildings in most studies, and can be used in this study.
- The housing database for the non-behaviour-related variables of the study consistently demonstrates evidence of significant consistency.
- Literature shows that wall and roof U-values are most influencing house energy use, followed by floor U-values, high performance window, air change rate, heating system efficiency, dwelling type, primary fuel type, heat source, floor area, domestic hot water cylinder (DHW) insulation, pipe-work insulation, internal temperature, window size, wall-floor-area ratio, DHW cylinder size and number of occupants.

Chapter 3: Irish Housing

3.1 Overview

This chapter gives an overview of the existing Irish housing stock by identifying its overall current state and possible future emissions reduction opportunities that are likely to influence future policy. First, it starts by identifying the main strands from the published national reports and aims to provide some insight regarding the profile of the housing stock. Second, it gives an account of the legislative context of the housing stock. Third, and finally, a number of possible futures are described that are capable of meeting the residential proportion of the 20% energy and emissions reduction targets of the government in the year 2020.

3.2 Profile of the existing Irish housing stock

This section summarises the main characteristics of the housing stock.

3.2.1 Generic characteristics

Number of dwellings

At the end of 2007 there were 1,678,829 recorded dwellings in Ireland of which 216,533 (13%) were vacant (CSO, 2008). This figure represents the number of private households in permanent housing units. Out of this figure, a total of 1,267,958 (75.5%) dwellings were built before 2002 (CSO, 2008) and it is these that are evaluated in this study for potential reductions in life cycle impacts. It should be noted that year 2002 represents the latest version of the housing survey carried out in Ireland for the existing Irish housing stock. The survey also represents the only source of available background data for the thesis. Further information on the significance of the year 2002 and Part L is provided in Section 3.3.4. Thus this study is based on the use of 2005 (i.e. year of survey of the housing database) input parameters of the housing database to evaluate the pre1960 – 2002 proportion of the existing Irish housing stock. The majority of dwellings are houses (93%) and flats (7%). The number of houses that were either demolished or otherwise removed from the housing stock increased from 6,500 in 1980 to 10,900 in 2003 (HSEU 2004) – a likely result of the age of the stock (see Table 3.1). The year 2003 represents the most current data; updated data was not found in literature.

Table 3.1: Dwellings demolished or otherwise removed from the stock (HSEU 2004)

Year	1980	1985	1990	1995	2000	2003
Number of houses	6,500	7,500	6,000	8,900	10,000	10,900

Dwelling type

The Irish National Survey of Housing Quality database included five main dwelling types. These include detached, semi-detached and terraced houses, and purpose-built and converted apartment. While detached houses account for 46% of the total housing stock, semi-detached house, terraced house, purpose-built apartment and converted apartment represent 27%, 20%, 5% and 2%, respectively (Watson and Williams, 2003). Figure 3.1 indicates distribution of the stock by dwelling type. As data for new dwellings (considered energy efficient for now) are considered outside the scope of the study, the composition of new dwellings was not considered for the purposes of this section.

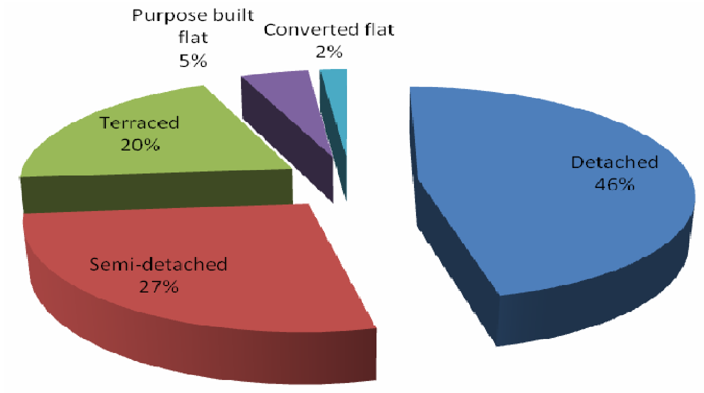

Figure 3.1- Irish housing stock by composition of dwelling type (Watson and Williams, 2003).

Age of dwelling

The Irish National Survey of Housing Quality (INSHQ 2001 – 2002) (Watson and Williams, 2003) divided dwellings into five construction periods. These are pre - 1960, 1961-1980, 1981-1990, 1991-1996 and post 1996. The five periods of construction were mainly influenced by the progressive building regulations over the years. For example, the first building regulations introduced in Ireland were in the form of 'draft' in 1979 (SEI, 2005). Similarly, mandatory building regulations were only introduced in 1991 and 1997 (SEI, 2005).

The age distribution of the housing stock indicates that pre1960 represents the highest distribution, followed by 1961-1980, post 1996, 1981-1990 and 1991-1996, respectively. These trends indicate a significant increase - partly a result of the building boom experienced in Ireland in the 1990s. Figure 3.2 indicates age distribution of the stock.

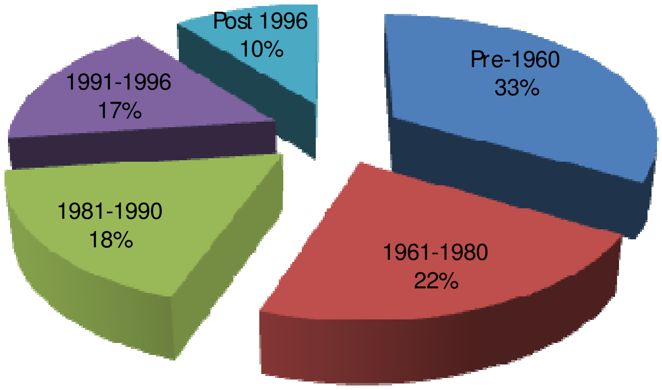

Figure 3.2: Age distribution of the stock (%) in 2002 (Watson and Williams, 2003)

Average floor area

The average floor area of a typical Irish household has significantly increased over the years. The average floor area for all units increased from 143.6 m^2 in 2002 to 164.3 m^2 in 2007 – a likely result of a combination of the economic boom experienced in Ireland in the 1990s, together with social wellbeing and wealth which are some of the factors associated with acquisition of larger properties (see Table 3.2).

Table 3.2: Average floor area of planning permissions granted 2002 – 2007 (CSO, 2008).

	2002	**2003**	**2004**	**2005**	**2006**	**2007**
Houses	**Unit** (m^2)					
Multi development units	n/a	118.7	119.1	124.5	128	132.9
One-off units (detached houses)	n/a	198.9	204.7	213.6	224.3	238
All units	143.6	147.1	147.8	149.1	158.7	164.3
Apartments	77.9	79.3	76.7	78.2	81.1	85.2

Household size:

The average household size in Ireland size was 2.9occupants/household in 2004 (HSEU 2006). This is higher than European average for the same period. In the EU27 Member

States the figure varies from a low of 2.0occupants/household in Finland, Latvia and Belgium to 3.2occupants/household in Slovak Republic, representing the highest within the community. The theory that explains the increases experienced in Irish housing is also true in the case of household size Figure 3.3 illustrates the average household size of Irish housing.

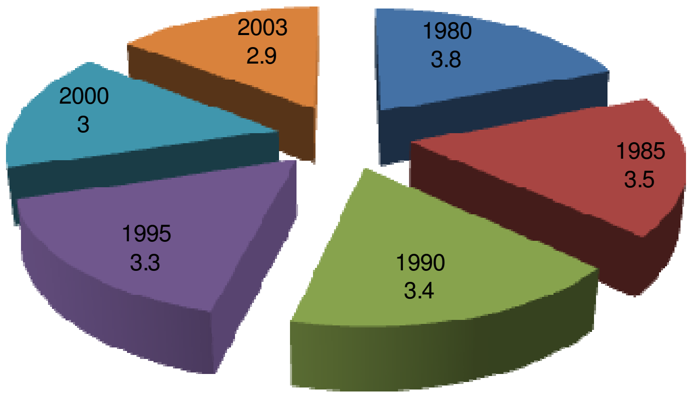

Figure 3.3: Average number of persons/dwelling (Adapted from HSEU 2004)

3.2.2 Fabric parameters

The fabric parameters of a building represent a predominant point of heat loss to its surrounding. According to Sustainable Energy Ireland (SEI 2004), a lot of Irish housing, especially those constructed before 1980 are energy inefficient, and potential heat loss areas of an un-insulated building include roof loss 30-35%, ventilation loss 25%, flue loss, window loss 15%, floor loss 7-10%, and loss through walls, 25-30%. This thesis therefore considers fabric improvements as significant in reducing energy and emissions of the Irish housing stock.

Wall insulation

Overall, around 76% of dwellings have wall insulation, and 24% have no wall insulation (Watson and Williams, 2003). Only about a third of the dwelling built before 1941 have wall insulation, while virtually all dwellings constructed after 1990 have one form of insulation or the other. Approximately 42% of Irish households are equipped with cavity-wall insulation (Clinch and Healy, 2003). However, the above data show that while a majority of houses have wall insulation a minority – 24% are un-insulated, raising concerns regarding poverty and health; improvement are clearly needed, especially when compared to 65%, 68%, 85% and 100% households with cavity wall insulation in similar countries - Denmark, France, Norway and Finland constructed during the same period, respectively (Eurostat 1999). Table 3.3 illustrates the various levels of envelope thermal insulation in Irish housing.

Table 3.3: Percentage of envelope insulation (Watson and Williams, 2003)

Insulated wall	Insulated roof	Floor insulation	Double glazed window
76	88	NA	69

Loft insulation

88% of dwellings have loft insulation, with only 96% of dwellings constructed since 1990 having insulated roofs, compared to 60% of those constructed before 1941. The difference between the proportion of roof and wall insulation has been attributed to the greater ease and lower cost associated with retrofitting roof insulation (Watson and Williams, 2003). Additionally, Clinch and Healy (1999) attributed the high level of roof insulation to the State-funded attic-insulation scheme of the 1980s.

Floor insulation

A search through the Irish National Survey of Housing Quality (Watson and Williams, 2003) reveals there are no data on the prevalence of floor insulation in Irish housing for those houses constructed during the period pre 1960 - 2002, as the INSHQ questionnaire survey was not designed to address highly technical and structural features (Watson and

Williams, 2003), and in particular as it was not possible to open up the floors in order to assess their insulation levels. However, a previous Irish study indicates that only 22% of Irish households have floor insulation (Clinch and Healy, 2003), also raising concerns regarding poverty and health; improvement are clearly needed, especially when compared to 63%, 88%, 100% and 100% households with cavity wall insulation in similar countries - Denmark, Norway, Finland and Sweden constructed during the same period, respectively (Eurostat 1999). Table 3.3 illustrates the various levels of envelope thermal insulation in Irish housing.

Air permeability

There is a paucity of data relating to the air-tightness characteristics of existing Irish dwellings (Sinnott and Dyer, 2011). For similar reasons to those given above, this also can be explained by the fact that the INSHQ questionnaire survey was not designed to assess detailed features. However, based on the available data from the housing database (EPSIH), it was assumed that overall, there is the presence of excessive air leakage, defined as an air change rate greater than 0.5 air changes per hour under normal air pressure found in only 37% of dwellings. This assumption is further supported as Sinnott and Dyer (2011), report on the air permeability of the existing Irish housing, and found the pre-1975, 1980's dwellings to be an average of $7.5m^3/hr/m^2$, and $9.45m^3/hr/m^2$, respectively.

Windows

For windows, a search through the Irish National Survey of Housing Quality (Watson and Williams, 2003) reveals that double glazing is the predominant window type in Irish housing, present in 69% of the total housing stock. Around 27% of Irish households are also equipped with draught stripping-windows, while 33% have draught stripping-doors. In addition to relevant improvements to the existing double glazed windows, the 31% single glazed windows of the stock should also be targeted for improvements.

3.2.3 Heating system parameters

In the previous section, the profile of the housing stock regarding its thermal insulation levels of the building envelope was discussed. This section looks at the current state of the house heating system parameters.

Irish household fuel mix

There have been significant changes in the mix of fuels used in the residential sector over the period 1990-2005. Table 3.4 below shows the shift from the use of open fires and solid fuel fired back-boiler heating systems to gasfired heating system. This can also be explained as new dwellings are likely to embrace cleaner fuels – in this instance oil, gas or even electricity, and in particular as there has also been a trend to convert existing back-boiler systems to either oil or gas (SEI, 2009).

Table 3.4: Residential energy use in Ireland from 1990 and 2005 (ktoe) (SEI, 2006)

Fuel	**1990**	**2005**
Coal	626	246
Peat	725	273
Oil	392	1166
Natural gas	117	607
Renewables (around 90% biomass)	45	16
Electricity	356	646
Total	2261	2954

Electricity fuel mix

The flow of energy in electricity generation indicates that natural gas remains dominant in the inputs of energy to generate electricity, representing 57% of total inputs, followed by coal 17.6, peat 11.8, renewable sources 7.7, oil 4.4 and electricity imports (net) 1.4%, respectively (see Table 3.5). As can be seen from the table the Irish electricity generation mix is still largely based on fossil fuels since 2005.

Table 3.5: Irish electricity generation fuel mix (%) in 2005 and 2009 (SEI 2007, 2009)

Fuel mix	**2005**	**2009**
	%	
Coal	28	17.6
Oil	15	4.4
Gas	40	57
Peat	10	11.8
Electricity Imports	3	1.4
Renewables	4	7.7

Penetration of central heating

Since 1987 the penetration of central heating in the existing Irish housing stock has significantly increased with 91% of dwellings having a form of central heating by 2005 (see Table 3.6). This increase can be explained by relatively greater efficiency associated with Central heating systems in comparison to individual room heating appliances. Central heating sytsems also provide increased levels of comfort in the form of prefered indoor temperatures, and in particular where there is a greater emphasis on the need for whole house heating. As can be seen the table indicates that oil-fired remains dorminant over the period, followed by natural gas-fired (28%) with electricity at only 3%, suggesting the need for a complete shift from solid fuels and oil to gas central heating systems.

Table 3.6: Penetration of Central Heating by Fuel Type in 2005 (CSO, 2006)

	Fuel type	1987	1995	2000	2005
		(%)			
1	Solid fuel	31	21	9	8
2	Electricity	1	2	4	3
3	Oil fired	12	25	39	46
4	Natural gas fired	4	14	25	28
5	Dual system	4	6	7	5
	Total Central Heating	52	68	83	91

Greenhouse gas emissions

Estimated national greenhouse gas emissions in 2005 grew by 25% during the period 1990 – 2005 (CSO, 2007), mainly a result of significant expansion of the economy (the economy grew by over 150%), coupled with a 20.3% rise in population same period (DCENR 2009). In 2005, the average dwelling was responsible for emitting around 7.6 tonnes of CO_2 (SEAI, 2006), raising concerns regarding Ireland's ability to meet existing obligations in emission reductions. In the UK, the average dwelling emitted approximately 5.9 tonnes of CO_2 for same period (Palmer and Cooper, 2011).

Quality of the housing stock

Ireland has been classified as a country among the least energy-efficient dwellings in Northern Europe (Brophy et al. 1999), and information from national reports (SEAI 2005, CSO 2005) indicates some delays in introducing mandatory energy efficiency standards in Ireland (SEAI 2005, CSO 2005). Based on the SEAI residential sector energy and CO_2 emissions report for 1990 – 2004 (SEAI, 2005) around 53% of the housing stock were constructed prior to the 1979 building regulations, which were in the form of a 'draft' and applied to state funded housing only (SEI 2005). However, progressive mandatory building regulations were introduced in 1991 and 1997, and those of 1997 were not signed into law until 2002, suggesting this gap in mandatory regulations must have significantly contributed to the above cited poor state of the housing stock.

3.3 Legislative context of Irish housing

This section discusses the overall legislative context of the housing stock.

3.3.1 National Energy Efficiency Action Plan (NEEAP)

The National Energy Efficiency Action Plan (NEEAP, 2009 - 2020) (DCENR), published in May 2009, sets out a national energy policy framework for the years 2009 - 2020. It is aimed at sustainable energy supply and use by addressing measures such as: reduction of energy-related emissions; the promotion of renewable energy resources; an integrated strategy for the sustainable development and use of bio-energy resources; optimisation of energy efficiency and energy savings across the economy; and acceleration of energy research, development and innovation programmes in support of sustainable energy goals.

The national energy policy framework is also intended to stimulate the enhancement of competitiveness of energy supply; integrated approach to delivery, together with the achievement of 20% savings in energy across all sectors by 2020 and setting target of 30% by 2020. Along this continuum, it is expected that building energy consumption will be reduced by at least 40%. Within this context, reductions are expected across all sectors as follows: 53% for residential, 16% for transport, 28% for tertiary and industry and 3% for electricity supply. The various reductions are expected to be achieved through the enforcement of the existing mandatory building regulations, financial supports and information/educative measures. Retrofitting the existing houses has been given a priority, especially as all new dwellings are expected to be constructed to passive house standard by 2020 (EC 2010).

3.3.2 EU Energy Performance of Buildings Directive (EPBD)

One of the mitigation efforts put forward by the European Commission for primary energy reduction in the sector is the Directive on Energy Performance of Buildings, the EPB Directive (2002/91/ EC), which came into force in 2002 and published in the EU Official Journal on 4 January 2003. The directive aims at improving the overall energy efficiency of new buildings as well as making it mandatory for large existing building to receive improvement once they are subjected to significant renovation. The directive emphasises the importance of climatic and local conditions as well as indoor climate environment and cost-effectiveness to improve the energy performance of buildings. The directive promotes measures such as methodologies for calculating the energy performance of buildings; application of performance standards on new and existing buildings; certification schemes for all buildings; and regular inspection and assessment of boilers/heating and cooling installations.

The EU Energy Performance of Buildings Directive (EPBD) has been transposed into Irish law since 2006, which has led to more stringent codes. These include: progressive building regulations (i.e. building regulations 2008 and 2011, the proposed building regulations 2013), the Dwelling Energy Assessment Procedure (DEAP) and Building Energy Rating (BER); these are describe below.

3.3.3 Dwelling Energy Assessment Procedure (DEAP)

The Dwelling Energy Assessment Procedure (DEAP) is the national methodology for rating building energy efficiency and involves assessing the energy required for space heating, ventilation, water heating and lighting, less savings from energy generation technologies. It is an asset rating technique based on building regulations compliance while its calculation method is as well based on standardized occupancy. The DEAP methodology is based on input parameters which are considered most important to annual energy usage and emissions. These include: size, geometry and exposure, construction materials, thermal insulation properties of the building fabric elements, dwelling ventilation characteristics and ventilation equipment, heating system(s) efficiency, responsiveness and control characteristics, solar gains through glazed openings, thermal storage (mass) capacity of the dwelling, fuels used to provide space and water heating, ventilation and lighting, renewable and alternative energy generation technologies. However, it does not allow the setting of occupant-related parameters, such as heating demand, hot water demand and appliances, but assumes standard use by typical households. Temperature set points are fixed.

According to Sustainable Energy Ireland (SEI, 2009), the DEAP is based on two types of label: 1) The BER Primary Label which is Scale A-G, expressed as kWh/m^2.yr (See Figure 3.4) and 2) BER Secondary Label which is expressed in kg of CO_2 per year calculated for the building (See Figure 3.5).

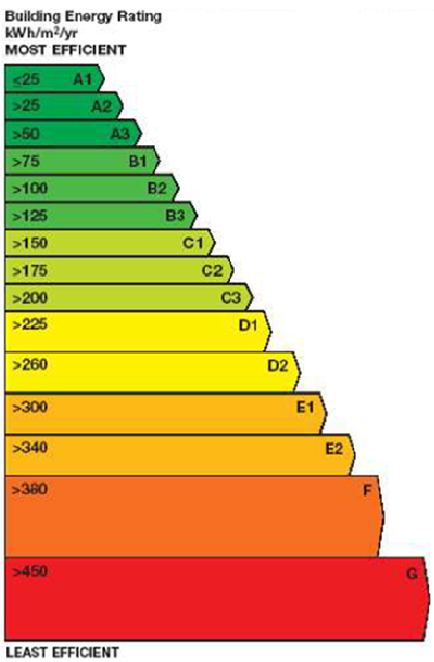

Figure 3.4: The Building Energy rating (BER) primary label – Energy label

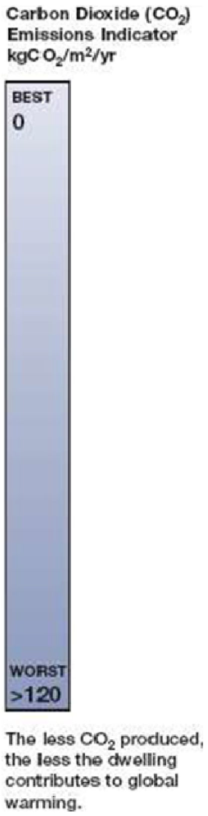

Figure 3.5: The Building Energy rating (BER) secondary label – CO_2 label

3.3.4 The new building regulations

Significantly, more stringent energy efficient and renewable energy building codes have been put in place by the new 2007 building regulations ('Part L'), which came into force in 2008. Building regulations 2008 were directed to achieve: reductions in energy consumption and CO_2 emissions by 40% (relative to the standards prescribed in the 2002 Building Regulations), the new building regulations 2011 have been established to achieve reductions in energy consumption and CO_2 emissions by 60%.

The proposals by Ireland for a further review of Part L of the building regulations, incorporating even more stringent codes, as identified in the government white paper is a testimony of the commitment of the government to sustainable development in the housing sector, and as a first step towards achieving the 20% energy and emissions reduction targets in 2020, relative to 2005 levels (DCENR, 2009).

According to the Department of the Environment, Heritage and Local Government (DEHLG) the principal objective of Part L of the Second Schedule to the Building Regulations is to reduce the use of fossil fuel energy and allied CO_2 emissions emanating from the operation of dwellings whilst still ensuring that occupants can achieve adequate levels of lighting and thermal comfort.

The Building Regulations (Amendment) Regulations 2008 contains the following new requirements: minimum overall energy and CO_2 performance standards: a new renewable energy contribution; a requirement for air leakage testing; and minimum efficiencies for oil or gas fired boilers.

3.3.5 Building energy rating:

As part of the Energy Performance of Buildings Directive (EPBD), the Building Energy Rating (BER) certificate was established by the Irish government which categorises the annual energy consumption of a building, and is expressed as primary energy consumption per unit floor area (kWh/m^2.yr) in a given year. BER is calculated using DEAP and is effectively an energy label, now required at the point of sale or rental of a building, or on completion of a new building. It is similar in style to those used on domestic appliances. The BER is also accompanied by a report on how building energy performance might be cost effectively improved. Further, the certificate includes an indication of CO_2 emissions arising from space heating, ventilation, hot water usage and lighting. Consequently, it will raise awareness of the contribution of dwellings to global warming.

The Building Energy Rating (BER) was introduced in phases, starting with new dwellings for which planning permission was applied after 1 January 2007, then non-domestic buildings for which planning permission was applied after 1 July 2008 and finally to all buildings, new or otherwise, when offered for sale or letting after 1 January 2009.

In terms of application, the scheme requires the vendor to provide an energy efficiency certificate, from a competent Assessor, showing the annual energy consumption (including cost) of the premises and the requirements necessary to reduce this consumption substantially, listed in efficiency terms, so at to ensure that the purchasing and upgrading of old housing is encouraged, particularly by first-time buyers. The purchaser is expected to compare house prices on the basis of this certificate and to determine energy efficiency investments to be made after purchase. In the case of local authority housing, schemes to upgrade the housing stock address energy efficiency and have a focus on alleviating fuel poverty.

Figure 3.6 below illustrates energy rating of Irish housing over the past four decades. The Irish residential sector experienced five construction standards from 1972 to 2002, representing the various contemporary building codes. The building codes, 'Regs 2008' and 'Regs 2010' represent the 2008 and 2010 building regulations, respectively which were yet to be released at the time of the publication of the above cited literature. Similarly, the building codes, 'LZC' represent the building regulations of the future expected to lead Ireland to near zero emissions dwellings. It can be seen that properties constructed to 1972 standards have an energy rating of around 340kWh/m^2.yr. Similarly, properties built to 2002 construction standards have an energy rating of around 150KkWh/m^2.yr, whereas properties built to 2008 building regulations have an energy rating of around 100kWh/m^2.a.

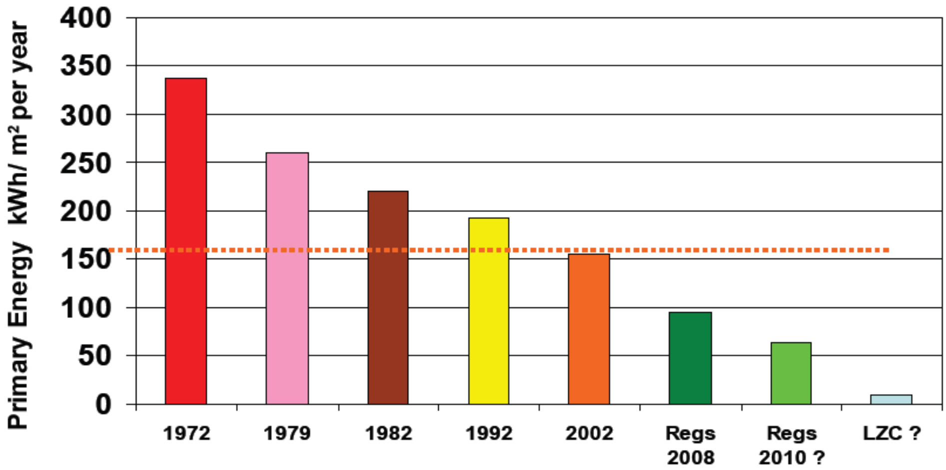

Figure 3.6: Construction standard/year. Source: (SEAI, 2009b)

3.4 The potential for energy reductions in Irish housing

Initially, and in addition to the BaseCase scenario, two house retrofit scenarios (Building Regulations and Passive House scenarios) were selected to assess the environmental impacts of intervention in the existing Irish housing stock. This present section looks at the various retrofit measures that can be applied to the housing stock based on the chosen retrofit scenarios in order to achieve the proportion of the residential sector of the 20% energy and emissions reduction targets for 2020 (DCENR 2009).

3.4.1 Fabric upgrades

The energy efficiency of the BaseCase dwellings can be improved by reducing heat can be improved by reducing the heating energy as far as practically achievable through the application of higher thermal insulation levels to the envelope elements. These potential improvement options include:

- Additional wall insulation
- Additional ceiling and rafter insulation
- Additional floor insulation

- Window replacement
- Application of sealing
- Heating system replacement and
- Renewable energy technologies including micro-generation devices

Air-tightness

It has been suggested that application of sealing to the thermal envelope of a building represents a cost-effective measure that can be undertaken without a major renovation (Harvey 2006). As air-tightness of a dwelling's envelope determines the amount of heat loss due to air infiltration the presence of excessive air leakage, air-tightness of the building envelope can be improved to minimise heat loss to air infiltration. Infiltration involves air exchange that occurs through cracks and small gaps in the external fabric elements that are not purpose-designed, such as spaces between window frames and external walls and small gaps around penetrations through the external envelope elements. Sealing can be applied to the no intervention house option to reduce air infiltration to an upper limit of 0.35ac/h, thereby complying with the current standard option. Similarly, the infiltration level can further be reduced to 0.25ac/h by applying further sealing all penetrations that are purpose designed to provide ventilation such as wall vents, trickle vents, flues, chimneys, etc, thereby complying with the passive house option whilst mechanical ventilation with heat recovery (MVHR) provides the required ventilation. Nemry et al (2010) applied three improvement options (additional roof insulation, additional façade insulation and new sealing to reduce ventilation) to the savings depend on location/region, and found that the measures yield at least an average of 20% improvement potential compared to the base case option.

External insulation

There are different options to improving the thermal performance of walls. External insulation can be applied to solid walls (EST, 2006). External insulation is insulation fixed to the existing wall exterior and covered with a water-proofing cladding; internal insulation involves a direct application of insulation board and plasterboard, or an internal timber studwork structure with insulation set between the studs plus plasterboard including a damp-proof membrane between the timber and internal wall surface. Thus, the thermal performance can be improved to achieve a U-value of $0.21W/m^2K$, thereby complying with the current standard option. This can also be further improved by additional insulation to achieve a U-value of $0.1W/m^2K$, thereby complying with the passive house option.

Cost effective insulation materials include rock mineral wool slabs. A further advantage of this insulation material is its lower embodied energy of production compared to rigid foam insulation boards made from polymers.

Cavity walls

The thermal performance of an un-insulated cavity wall can be improved by filling the cavity with insulation to achieve a U-value $0.35W/m^2K$. However, typically additional internal or external insulation must be applied to achieve a U-value of 0.21 corresponding to the current standard. Insulation can be applied by injection through holes or slots made in the inner or outer leave of the wall (Roberts, 2008). In the case of a partial fill, insulation is applied either internally or externally to attained the above level see section solid walls above). To achieve insulation level to the passive house standard option, additional insulation can be applied to achieve a U-value of $0.1W/m^2K$.

Cost effective insulation materials that can be undertaken include semi-rigid slab made from glass mineral wool. Similarly, a further advantage of this insulation material is its lower embodied energy of production compared to rigid foam insulation boards made from polymers.

Pitched roof insulation

There are two methods of insulating pitched roofs - at the ceiling level between the joists, or between the rafters.

Ceiling insulation

The majority of Irish dwellings have some form of roof insulation. This can be improved by adding insulation to achieve a U-value of 0.16 W/m^2K, thereby complying with the current 2011 building regulations. This can be further improved by applying additional insulation to achieve a U-value of 0.1W/m^2K, thereby complying with the passive house option.

Rafter insulation

The above theory for ceiling insulation is also through for rafter insulation but the amount of insulation applied is dependent on the level of existing insulation attained, and the thermal conductivity of the insulation (EST, 2007).

Cost effective insulation materials include glass mineral wool rolls and for rafter insulation, a vapour barrier membrane can be applied to the face. Like in the case of cavity walls, a further advantage of this insulation material is its lower embodied energy of production compared to rigid foam insulation boards made from polymers.

Floor insulation

The two ground floor construction types in Irish housing are solid floor and suspended timber floor.

Solid floor: Installing insulation in existing un-insulated solid floors involves removing the existing concrete slab, laying insulation boards and pouring concrete floor on top. An alternative is to retain the existing floor and install insulation and a new concrete deck on top of the existing. However, it should be noted that the limitation of the latter option is that ground floor headroom will be reduced and other construction details, such as door height, etc may be affected. The existing solid floor insulation level of the no-intervention option can be improved by increasing insulation to achieve a U-value of 0.21 W/m^2K, thereby complying with the current standard option. This can further be improved by applying additional insulation to achieve a U-value of $0.1W/m^2K$, thereby complying with the passive house option.

A common means of improving the thermal performance of suspended floors is by placing insulation underneath in the space between the joists. In the case of suspended timber floor, insulation thickness can be easily increased to achieve a U-value of $0.21W/m^2K$. The amount of insulation applied is dependent upon the thermal conductivity of the new and existing insulation (if any). For the passive house option, the U-value can still be further reduced to $0.1W/m^2K$ or lower.

For the two types of floor construction, cost effective insulation materials include rigid water-resistant insulation with R-value greater than $2.5m^2K/W$ and rigid insulating boards for solid floor and suspended timber floor, respectively (EST, 2007). These two types of insulation are considered cost effective when compared with mineral wool because they are most appropriate for the application being considered.

Windows

As air leakage around the window sealing has the greatest impact on window heat loss, existing single/double glazed windows can be replaced with factory triple-glazed windows with a low-emissivity coating, and 2 gaps with air, to achieve a U-value of 1.6, thereby complying with the current standard option. In addition to the above, these windows can be further improved to high performance triple-glazed windows that incorporate integral draught stripping, to achieve the passive house standard (Pilkington manufacturers 2012).

Doors

New solid doors can be installed, and insulated with polyurethane rigid foam to achieve a U-value of 1.6W/m^{2}K, thereby complying with the current standard option. This can be further improved to achieve 1.0Wm^{2}K (EST 2010), thereby complying with the passive house option.

3.4.2 Heating systems upgrades

In a typical dwelling, space and water heating accounts for most of the energy used and corresponding GHG emissions. A significant proportion of this consumption can be reduced by substituting existing conventional heating systems with low-emissions technologies.

The efficiency of a boiler plays a major role in determining the amount of energy use during the operation phase of the building. The heating system can be upgraded to meet current standard regulations by substituting the existing gas/oil-fired conventional boiler with condensing, instantaneous water heating boiler (90% seasonal efficiency). Thermal losses from the hot water cylinder can be reduced by changing from a factory-applied PU-foam (having zero ozone potential and a minimum density of 30kg/m^3) with a coating thickness of 30mm to 50mm. Solar hot water heating with a 4m^2 flat plate system can provide a significant proportion of the households' water requirements (EST, 2006, 2007, 2010). The proper application of these measures can achieve compliance with current building regulations.

In addition to the above, further measures are needed in order to meet passive house standards. These include ground source heat pumps for space heating or wood-fired district heating (i.e. CHP); air source heat pump in houses with limited land space (EST, 2006, 2007, 2010); and a whole dwelling mechanical ventilation with heat recovery (MVHR) (i.e. 88% heat recovery and 0.6W/l/s specific fan power) which provides ventilation including further provision of space heating demand (maximum 15kWh/ m^2yr) by electric resistance heating in the supply air of the mechanical ventilation and heat recovery system (Wall, 2008). Other measures that can be applied include PV generation with $8m^2$ mono-crystalline panels comprising an array of four panels at approximately $2.0m^2$ per panel; and increasing DHW cylinder insulation from the full recommended thickness of 50mm to 75mm of a factory-applied PU-foam (having zero ozone potential and a minimum density of $30kg/m^3$). As in the case of the current standard option, provision of advanced controls for the heating system will be required in order to maintain the benefits of the upgrades.

3.5 Improvement implementation initiatives

In Ireland there are several government initiatives aimed at delivering energy and GHG emissions reductions in existing housing. These initiatives are designed to complement legislative measures or sometimes serve as alternatives to them. The delivery of the budget allocation for these initiatives is usually delegated to agencies (Clarke et al., 2008), such as Greener Homes Scheme, the Home Energy Saving (HES) Scheme, and the Warmer Homes Scheme. The Greener Homes Scheme focuses on providing assistance towards purchasing new renewable energy heating systems for existing homes first occupied before 30th June 2008. The Home Energy Saving (HES) Scheme provides grants for improving the energy efficiency of Irish households in order to reduce energy use and costs as well as greenhouse gas emissions. The Warmer Homes Scheme assists in the implementation of a national plan of action, aimed at systematically addressing the problem of fuel poverty.

However, with 7.4% and 8.8% increases in residential overall primary energy demand and energy-related CO_2 emissions respectively in 2008 (heat and electricity) compared to 2007 (SEI 2009), it is likely that future energy efficiency upgrades in the existing Irish housing stock will rely on regulation and enforcement including improved performance of the non-regulatory measures. For example, some of the elements of the EPBD earlier discussed such as the 2008 and 2011 building regulations and the BER are mechanisms for benchmarking minimum mandatory standards for existing dwellings (Clarke et al. 2008). By focusing on a combination of regulations and enforcement, fiscal incentives and information/education, it is possible to attain the desired change in the residential sector.

3.6 Conclusions to Chapter 3

The main findings from this chapter are summarised below:

- The pre1960 – 2002 portion of the existing Irish housing stock represents the only source of available background data for the thesis.
- A significant proportion of the housing stock was built during the delay in introducing mandatory building regulations and may therefore be lacking necessary energy efficiency measures.

- Household size is higher than EU average, and represents an important factor in deciding residential energy use.
- The higher average floor area, especially given by the increasing trends indicated in Table 3.2) is likely to lead to increased energy consumption in most dwellings.
- A lot of Irish housing, especially those constructed before 1980 is energy inefficient, and a majority of the pre1960 - 2002 portion of the housing were built before this period.
- Ireland has been classified as a country among the least energy-efficient dwellings in Northern Europe.
- Oil represents the main fuel used for heating in Irish housing, and there has been a switch away from the use of open fires and solid fuel fired back-boiler heating systems to gas-fired heating system. A clear strategy is needed as quickly as possible to shift from solid fuels and oil to gas-fired central heating.
- Improvements are clearly needed, especially when compared to similar housing stocks in EU.
- Overall, fabric insulation is essential in most dwellings for energy efficiency retrofitting whilst priority should be given to floor insulation, especially as only 27% of houses have this measure.
- The inventory of the retrofit measures that required to be focused on includes fabric upgrade (application of sealing to the thermal envelope of the building, external and internal insulation, ceiling insulation, rafter insulation, floor insulation, replacement of windows and insulation of new solid doors), heating system upgrades, and application of micro-generation devices. Existing policy measures on these retrofit

measures should be reinvigorated if the residential portion of the year 2020 emissions reduction targets is to be achieved.

- The national energy policy framework 2007 – 2012 sets out clear objectives to achieve 20% energy and emission reductions compared to 2005 level by 2020, and setting target of 30% by 2020.
- The transposition of the EU Energy Performance of Buildings Directive (EPBD) into Irish law since 2006 has led to more stringent codes such as progressive building regulations (i.e. building regulations 2008 and 2010, the proposed building regulations 2013), the Dwelling Energy Assessment Procedure (DEAP) and Building Energy Rating (BER).
- Construction standards have been improving since 1972.
- The BER playing the dual role of regulation and information including financial incentives in the form of the provision of low interest loans may also assist convert information on the value of dwellings into lifelong energy efficiency upgrades, based on a market change technique. It should be noted that the provision of low interest loans is considered important by this study given by the current state of the economy not only in Ireland, but in most advanced economies.
- The EU Energy Performance of Building Directive (EPBD) has already provided some of the basis for a market change system whilst the EPBD appears to be succeeding given by the level of its adoption by Member States. Moreover, enforcing and updating the existing building regulations is of essence.
- Despite the availability of various financial incentives including information/education by government to support energy efficiency improvements, residential energy consumption and emissions have been on the increase. It is likely

that future energy efficiency upgrades in the existing Irish housing stock will rely on regulation and enforcement including improved performance of the non-regulatory measures.

Chapter 4: Research Methodology

4.1 Overview

Initially, representative archetypes of the existing Irish housing stock were developed. The methodology for developing representative archetypes involves a literature review of studies to identify the most important variables which explain energy use. A multi linear regression analysis (MLRA) of the housing database was performed to identify the most relevant variables associated with energy consumption. Representative parameters were identified using a statistical analysis of the distributions for each key variable. Knowledge of housing construction details were used to choose corresponding construction details. Coincident groups of parameters and construction details were identified using cluster analysis; this led to the classification of 13 representative house archetypes (Famuyibo et al, 2012).

The energy use and associated emissions were then modelled for each archetype and these were scaled up to estimate emissions from the total housing stock. A hybrid-LCA methodology was used to assess the impacts of operation, maintenance, retrofit and disassembly phases of each archetype to give a ‘BaseCase’ for energy and emissions. The hybrid-LCA involves a combination of methods and databases. In calculating the hybrid energy and emissions, process analysis was used for material quantities for which process emissions intensities can be applied. On the other hand, input output (I - O) analysis was used for materials quantities for which input-output emissions intensities can be applied.

Two scenarios for upgrading the housing stock model were developed – ‘meet current building regulations’ (Building Regulations standard) and 'meet anticipated future regulations' (Passive House standard); involved identifying and modelling a range of interventions which achieved energy ratings equivalent to the Irish 2010 building regulations and passive house standards, respectively. These upgraded stock models were then reassessed as before to estimate their impacts on energy and emissions. The results of each of the retrofitted scenario were compared relative to the Basecase scenario. In addition, the results of the Current Regulations scenario and the Passive House scenario were also compared.

Where necessary, the results of the study were also expressed according to national and international sources of energy and emissions (see Chapter 1). Overall, it should be noted that in the remaining part of this thesis that where 'energy' or 'emission' is mentioned, primary energy and primary energy-related CO_2-equivalent emissions are implicit.

Life cycle costs (LCC) were estimated for each of the archetype dwelling across the differing house scenarios. These include discounted LCC of ordinary maintenance of the BaseCase scenario dwelling and those of the retrofitted scenarios. The net present value (NPV) of each of the archetype house was calculated across operation, maintenance and repair, retrofit and disassembly phases. The discounted LCC of each of the archetype dwelling across the differing house scenarios was then calculated as the summation of the NPVs across life cycle phases.

A quantitative estimate of CO_2 abatement potential and the net societal costs or savings per tCO_2-eq of avoided greenhouse gas emissions of retrofitting the existing Irish housing stock were evaluated. CO_2 abatement potential was calculated for the two retrofitted options – as the difference between emissions from the BaseCase scenario and emissions from the corresponding retrofitted scenario. Similarly, retrofitting costs of abatement were calculated for the retrofit scenarios. The marginal abatement cost of a given retrofit scenario was calculated as the difference between the full cost of the retrofitted scenario and the full cost of the BaseCase scenario divided by the difference between emissions from the BaseCase scenario and emissions from the corresponding retrofitted scenario. Figures 4.1 and 4.2 below illustrate the overall methodology used in the study.

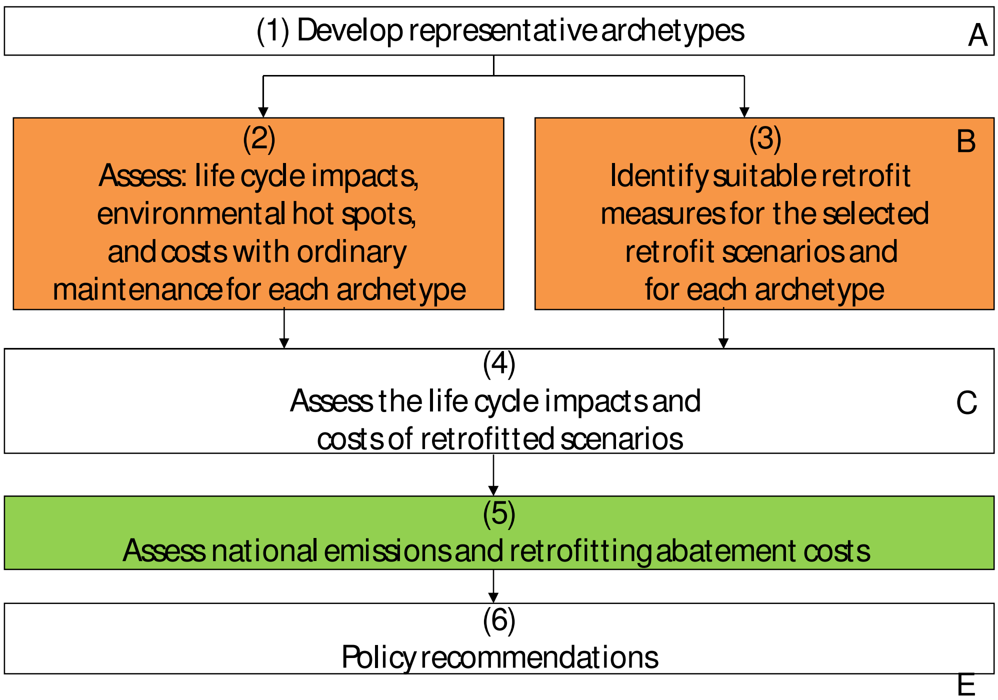

Figure 4.1: Research Methodology

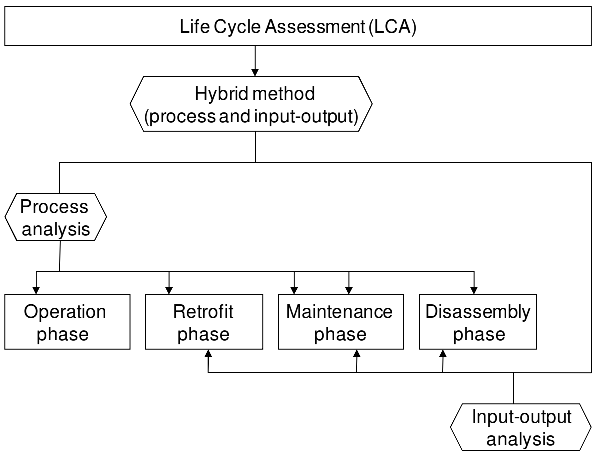

Figure 4.2: Combination of methods and databases

4.2 Developing representative archetypes

In the previous section, the summary of the methodology used in the thesis for developing archetype was discussed. In this section, a detailed discussion of this methodology is provided.

The broad methodology being employed in this study involves the following steps (see Figure 4.3):

a. Checking that the representativeness of the housing database used in the study

b. Using studies reported in literature to develop a full set of housing stock variables which impact energy use**.**

c. Conducting a statistical parametric analysis to identify and rank the key variables affecting energy use which are particular to the Irish housing stock.

d. Developing representative archetypes based on the prevalence of parameters which are typically present for each key variable.

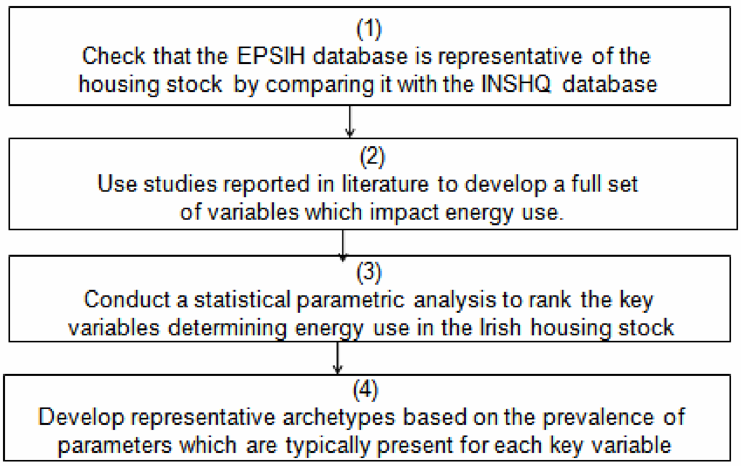

Figure 4.3: Methodology for developing archetypes

4.2.1 Checking the representativeness of the EPSIH housing database

To develop representative archetype houses, a housing database was required. In this study, two databases have been useful in the development of archetypes – the Energy

Performance Survey of Irish Housing (2005 EPSIH) and the Irish National Survey of Housing Quality (2001-2002 INSHQ). While the EPSIH was predominantly used in the current study, INSHQ was used to check the representativeness of the EPSIH. While the overview of the EPSIH and the INSHQ has been undertaken in Section 2.7 under literature review, this section discusses the procedure used in checking the representativeness of the EPSIH.

Given the wealth of technical detail in the EPSIH database, it was decided to use this as the basis for developing representative archetypes. However, given its small size, its representativeness was first checked against the larger INSHQ database. All variables common to both databases were therefore compared.

Fabric element insulation: The insulation of fabric elements recorded in the INSHQ include insulated wall, insulated roof, and double glazed windows. The penetration of insulation in the INSHQ, as shown in Figure 4.4, is greatest with roof insulation. When data on insulation from both samples were compared, the INSHQ has 15.3% more roof insulation than the EPSIH. While the INSHQ indicates 2.7% more insulated wall than the EPSIH, the EPSIH indicates 5.7% more double glazed windows.

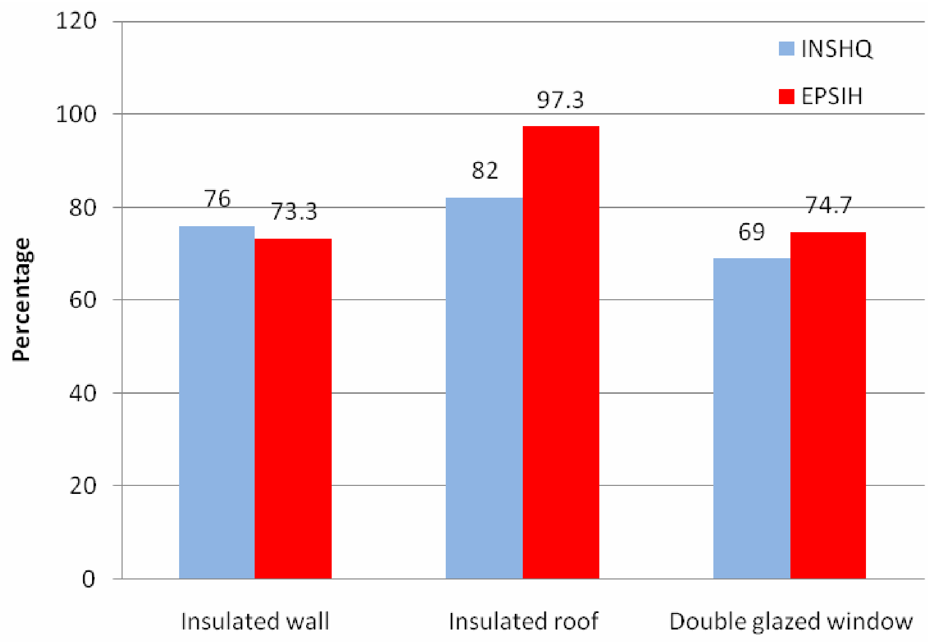

Figure 4.4: Comparison of fabric element insulation for both surveys

Dwelling type: The main dwelling types in Irish housing are detached, semi-detached, terraced, purpose-built apartment and converted apartment. Whilst detached dwellings, at 50%, represent the most common house type in the EPSIH, in the INSHQ is 46.1%. All dwelling type characteristics with the exception of converted flats indicate modest differences within the two datasets of 3.9%, 0.2% and 2.1% for detached houses, terraced houses and purpose built apartments, respectively; and 4.5% and 1.1% for semi-detached houses and converted apartments. Figure 4.5 illustrates the percentages of different dwelling types in both samples.

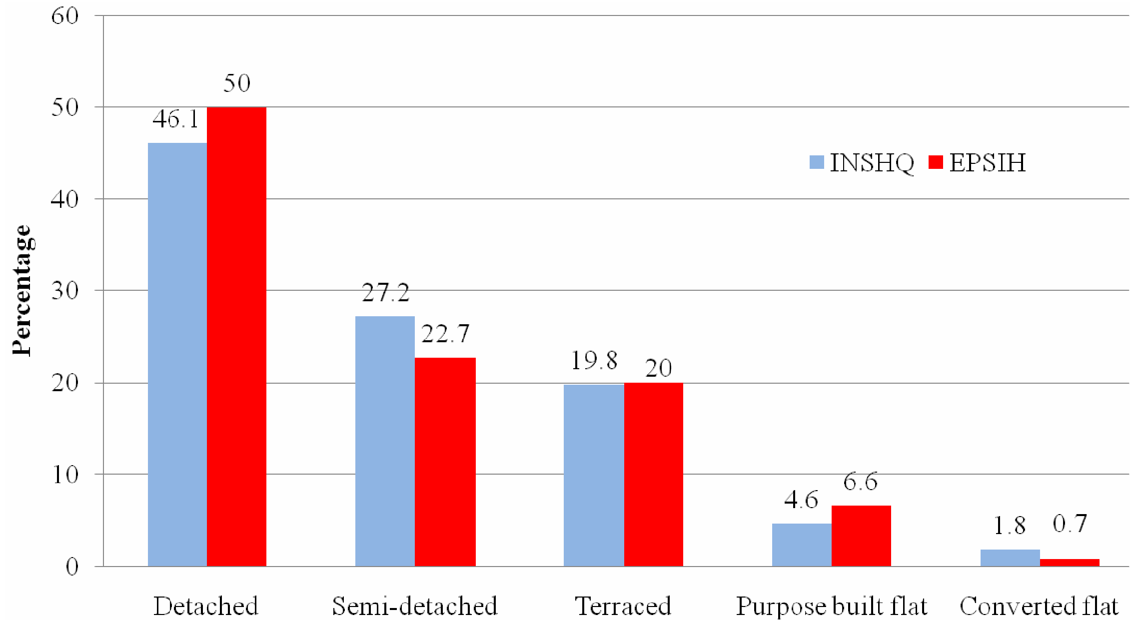

Figure 4.5: Comparison of dwelling types for both surveys

1. *Period of construction:* The INSHQ recognises five periods of construction in the Irish housing stock. These include pre-1960, 1961-1980, 1981-1990, 1991-1996 and post 1996. However, the EPSIH recorded these periods as pre-1960, 1961-1980, 1981-1990, 1991-1996 and 1997-2002. Pre-1960 and post 1996/1997-2002 are the most "busy", accounting for 29% and 33.3% of the INSHQ and EPSIH, respectively. A comparison of the data of both samples indicates a significant difference as the INSHQ has 16.3% more dwellings than the EPSIH for the period 1981-1990. However, other construction period characteristics for both samples indicate significant consistency. For example, while the INSHQ indicates 3%, 1% and 4.7% more dwellings than the EPSIH for the periods pre-1960, 1961-1980 and 1981-1990, respectively, the EPSIH shows 2% and 16.3% more dwellings for 1991-1996 and post 1996/1997-2002, respectively (See Figure 4.6). This can be explained as there would have been an increase in the number of dwellings completion in the

two years between the two surveys. It should also be noted that the post 1996/1997-2002 was the most “busy”, accounting for 33.3% of the EPSIH.

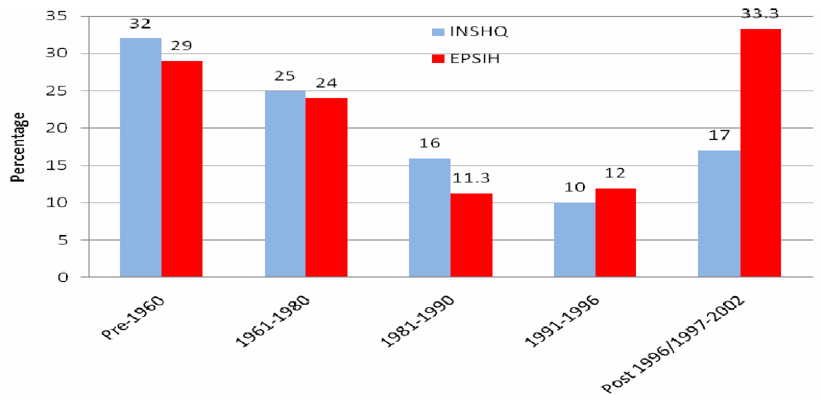

Figure 4.6: Comparison of the periods of construction for both surveys

Fuel type: The INSHQ indicates five main primary heating fuel types in Irish housing. These include oil, gas, peat, coal and electricity. The data for gas-fired central heating indicates the most significant difference, and representing 11% more users for the EPSIH, suggesting there would have been an increase in the number of central heating in the two years between the two surveys, especially as the 1997 building regulations were only signed into law in 2002. While the INSQH has estimated the total for oil central heating to be close to 50% of all household, it should be noted that the oil fuel mix represents the total for both kerosene and diesel oil in the two surveys. Overall, the comparison of the remaining data for both samples indicates that the INSHQ has 3%, 1% and 1% more oil-fired, coal-fired and electricity-based central heating than the EPSIH, respectively. The EPSIH has 1% more peat-fired central heating than the INSHQ (See Figure 4.7).

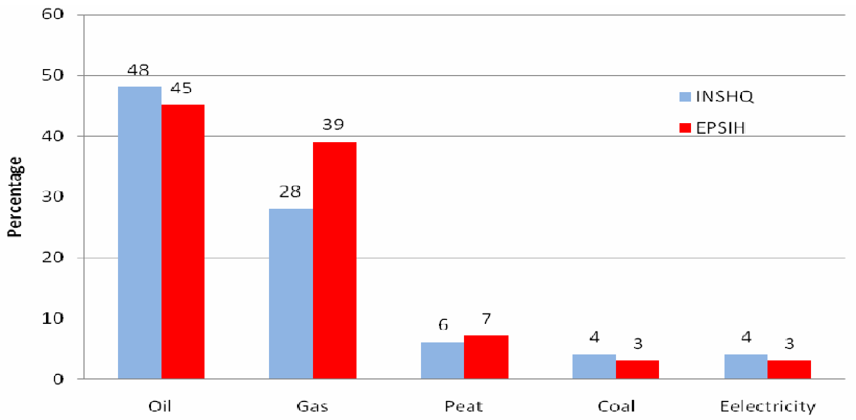

Figure 4.7: Comparison of the fuel type datasets for both surveys

As can be seen above the conclusions regarding the representativeness of the housing database for the non-behaviour-related variables of the study consistently demonstrate evidence of significant consistency. The modest differences in the datasets of the INSQH and the EPSIH are not likely to have a significant effect on the results of the study.

4.2.2 Step 2 Choice of variables for multiple linear regression analysis (MLRA)

In this step, the methods used to choose variables for use in the multi linear regression analysis that was performed is discussed. This is followed by a detailed explanation of the statistical approach (MLRA). Subsequently, the detailed methods used for developing archetypes are discussed.

The choice of variables for the MLRA was informed by the need to include all variables that will ordinarily contribute to the prediction of household energy use (Field, 2009). These variables include the 17 variables identified in literature based on the review of energy efficiency studies (Section 2.8 of Chapter 2 refers) as well as all variables in the EPSIH housing database that will ordinarily contribute to the prediction of household energy use. This procedure resulted in a total of 25 variables (17 variables plus additional six from the EPSIH). These include Wall U-values (W/m^{2}K), Roof U -values (W/m^{2}K), Floor U -values (W/m^{2}K), Window U -values (W/m^{2}K), Air Change Rate (ac/h), Internal Temperature (^{o}C), House Volume (m^3), Heating System Efficiency (%), Dwelling Type, Temperature controls, Household composition, DHW Cylinder Insulation Thickness (mm), Cylinder Size (litre), Pipe-work Insulation (mm), Floor area (m^2), Wall-to-floor area, Primary fuel, Heat source, Window size (m^2), Electricity Tariff rate (day/night/standard), Draughts (persistent draughts/some draughts/no draughts), Humidity (typically damp/occasionally damp/typically dry), Immersion Heater Weekly Frequency, Typical Weekly Occupancy Pattern (heating season) (low/medium/high) and Number of Storeys.

4.2.3 Step 3 Statistical Analysis

In Step 3, a statistical analysis of the importance of the above 25 household variables to the Irish housing stock using the EPSIH database is discussed.

Depending on the type of research question that is required to be addressed and the available data, there are many statistical approaches to exploring relationships among variables. These include: correlation, partial correlation, linear regression, logistic regression and factor analysis. Multi linear regression analysis (MLRA) permits prediction of a single dependent continuous variable from a cluster of predictors. This technique can be used to test the predictive influence of a set of variables and to evaluate the comparative input of each individual variable. MLRA can be used to explore how far predictors are able to predict influence on a dependent variable. For example, in research questions involving housing stock modelling, MLRA can be used to explain the degree to which household variables (predictors) affect, say, energy use (dependent variable). Overall, the technique indicates the level of variance of the dependent variable (energy use) that can be explained by the predictors. While it shows the influence of the comparative inputs of the individual independent variables, it also indicates the overall statistical significance of the results of the model, and each of the independent variables.

An initial MLRA was performed using all the 25 variables in order to identify and exclude variables with high bivariate correlations in the analysis. In an MLRA, it is possible for two or more variables to have high bivariate correlations due to overlap (Pallant, 2006), which may result in negative coefficients of determination and reduced the number of predictors. Therefore, it was decided that only one out of any two or more variables with a high bivariate correlation will be used in the analysis. For example, there are high bivariate correlations between house volume, floor area and window area. While all variables with high bivariate correlations were used in turn for the initial MLRA, the variables with the highest coefficient of determination (R^2) were chosen for the final MLRA. Therefore, all variables with high bivariate correlations were excluded from the MLRA. The number of variables for the MLRA was therefore reduced to 20.

To enhance the explanatory ability of the outcome of the MLRA model, the use of dummy variables within the analysis was undertaken. This further increased the number of variables used for the final analysis from 20 to 31. Several of the variables were disaggregated along their individual categories. For example, dwelling type was categorised into detached house, semi-detached house, end-terraced house, mid-terraced house, purpose-built apartment and converted apartment. Detached house was assumed to be dummy variable for the dwelling type variable and was therefore excluded from the final MLRA. Similarly, the selected dummy variables for the categorical variables were excluded. Thus, the 31 variables included in the final analysis are Wall overall U-value (W/m^2K), Roof overall U-value (W/m^2K), Floor overall U-value (W/m^2K), Window overall U-value (W/m^2K), Air change rate (ac/h), Internal temperature (^oC), Semi-detached, Mid-terrace, End-terrace, Purpose-built apartment, Converted apartment, Heating system (%), House volume (m^3), Number of storeys, Household composition (2adults, 2 children), Household composition (3 adults, 3 children), Household composition (4 adult, 4 children), Household composition (5 adult, 5 children), Cylinder insulation thickness (mm), DHW cylinder size (litre), Pipe-work (mm) (insulated), Thermostatic radiator valve control (trvc), Fulltime temperature control (fttzc), Typical weekly occupancy pattern (Heating Season) (medium), Typical weekly occupancy pattern (Heating Season) (high), Immersion heater weekly frequency, Electricity tariffs (day/night), Draught (persistent), Draught (some), Humidity (Occassional damp) and Humidity (typically damp).

To identify the importance of the above variables in Irish housing, MLRA was undertaken using a statistical computer package (SPSS) (Field, 2009). All 31 variables were regressed as independent variables against Total Energy Use, as the sum of fuel and electricity purchased (in kWh) for the purposes of space and water heating, lighting and appliances.

4.2.4 Step 4 - Archetype formation methodology

Once the full set of key variables of energy use was identified, a set of archetypes was developed. The following characteristics were used to differentiate the archetypes.

1. Those features that are more found to be significant in estimating energy use the parameters of which are likely to be related to the building regulations effective at the time of construction.

2. The recorded characteristics of construction detail or construction type. For example, wall construction types such as cavity walls (timber walls are considered to be included in the cavity wall category), and single-leaf wall (hollow block walls are considered to be included in this category); Roof insulation types: ceiling insulation, and rafter insulation; Floor construction types: solid floor and suspended timber floor; and Window insulation types: single glazing, double glazing and low-e glazing. It should be noted that construction detail has been considered important because two dwellings with the same dwelling type may not necessarily have the same construction detail, and hence differing impacts on house energy use (e.g. single solid wall versus cavity wall).

The above selections are likely to generate a matrix that allows for a large number of categories which can be described as house archetypes. However, in order to comply with the primary aim of the study, and in particular as a large number of archetypes would make description, stock analysis, and the assessment of new scenarios difficult (IEA, 1998), the number of archetypes can significantly be reduced using the following three principal techniques:

Frequency histograms were used to choose parameters which are representative of the key variables. Using the data in the EPSIH database, frequency histograms were generated in order to identify concentrations of particular values, thus allowing representative values ("typical values") to be chosen. In order to ensure that the representative values represent well-defined centres of the distributions, the approach adopted was to choose: (1) modes of symmetric distributions of key variables; and (2) means or medians or modes of skewed (non-symmetric) distributions (depending on the summary and characteristics of the dataset of the individual distributions) of key variables. Here mode is the preferred central value since it will be representative of a common construction type; mean and median may yield values which are not.

Representative parameters and knowledge of construction details/building regulations were used to choose representative construction details. Using the above chosen representative U-values for Wall and Roof U-values and based on knowledge of construction details/building regulations, representative construction details were then chosen.

Scatter-plots were then created for pairs of variables and coincident (clustered) values were identified. In each revisions of the building regulations, minimum values are frequently specified for all fabric elements and heating systems. When the regulations are revised, these may all change, leading to similar parameter sets for buildings built under the same regulations. Therefore it is expected to see some clustering of variables in the sample. The identification of these clusters would greatly reduce parameter combination among key variables. Therefore, in this procedure, variables that are expected to be correlated were paired and scatter plots were generated for each of these pairs using their distribution data as recorded in the EPSIH. Their clusters in the scatter-plots were then identified.

The resulting key variables and clusters of construction details served as a basis for defining archetypes. Cluster values were then combined into parameters as much as possible based on the chosen representative values in the frequency histograms.

The above procedure was repeated for all paired variables in succession.

4.3 Hybrid-LCA methodology

This section discusses the methodology used in calculating the energy and emissions attributable to the existing Irish housing stock across the different house scenarios using the results of the developed 13 archetypes.

It has been previously discussed in Chapter 2 that there are different environmental assessment techniques that can be combined to perform stock modelling. This approach is regarded as best practice in life cycle primary energy and primary energy-related emissions analysis (*inter alia* Moriguchi et al, (1993); Suh *et a.*, 2000; Joshi, 2000; Lenzen *et al*, 2002; Crawford, 2005 and Suh *et al*, 2005).

To allow all energy and emissions across life cycle phases and house retrofit scenarios to be evaluated, a model of the existing Irish housing stock incorporating a process-based LCA hybrid method developed. Furthermore, these impacts must also consider the split between imported and domestically generated emissions, especially as relates to national environmental balance. These are described in detail below. First, the process analysis technique is described, and then input-output and hybrid approaches are discussed.

4.3.1 Process-LCA methodology

The methodology has been carried out in accordance with: ISO 14040 (2006) - Environmental Management- life cycle assessment-Principles and framework; and ISO 14044 (2006) - Environmental Management- life cycle assessment- Requirements and Guidelines. It should be noted that the ISO 14040, 41, 42 and 43 were ‘rolled up’ into the above two standards. This section now discusses the process LCA methodology used in study.

Functional unit

On the basis of the literature review of studies on functional unit in Chapter 2, two functional units are proposed in this study: the functional unit '1 m^2 total heated floor area' is chosen as the most adequate functional unit to compare the results of the LCA because it makes comparison with the results of other studies possible, and in particular it is the functional unit used in most studies. The functional unit of study represents the use of 1 m^2 of the building's living and bedrooms space over the period of one year. A second functional unit, 'per dwelling is also chosen as the most favourable to policy making, especially as it will be useful in prioritizing residential upgrade projects within any available limited funding.

Environmental impact categories

In this study, global warming potential (GWP) and primary energy (PE) as environmental impact categories are assessed for the different archetype representative dwellings. They are chosen on the basis of literature; international agreements; feasibility; the most significant impact category attributed to the building sector; and regional and national policies, and in particular as most environmental indicators published by Irish government agencies focus on greenhouse gas emissions and primary energy. In addition, primary energy is regarded as comprehensible measure for typifying the life cycle of a building system, and in particular as it represents a significant indicator for a variety of environmental impacts.

Characterisation

As a detailed discussion of characterisation has been previously carried out in Chapter two, in this study, the characterisation of the environmental impact, global warming, an operational Guide to the ISO Standards 2001 (CML2001) also referred to as the classical impact characterisation method of CML (Centre for Environmental Science, Leiden University) is used. Once all relevant life cycle inventories are generated and used as inputs into GaBi software tools, the quantitative estimation of life cycle impact indicators or the evaluation of the impact assessment results are automatically generated.

Building system

The building system represents the total system of processes required for the building (Blengini, 2009), together with its linked material and energy flows. In this study, the building system comprised unit processes, each of which indicates one or several activities, such as extraction/mining of raw materials, refinement, processing and manufacturing of materials, operation, retrofit, maintenance, and disassembly of the building including all associated transportation. Across the continuum of processes, data are recorded on the inputs of natural resources, the emissions, waste flows, and other environmental exchanges. These environmental exchanges to and from the building system are directly linked to one of the building flows of the unit process. Furthermore, all unit processes are linked through intermediate building flows. Figure 4.8 illustrates study house system boundary (life cycle diagram). While the main oval solid shaped represents house system boundary, dashed dot arrows represent relationship between several life cycle phases, such as waste management of materials of disassembly. It should be noted that these links are outside the scope of this study but represents potential negative and positive values of recycling. Similarly, Figure 4.9 represents an example of a unit process within a building system.

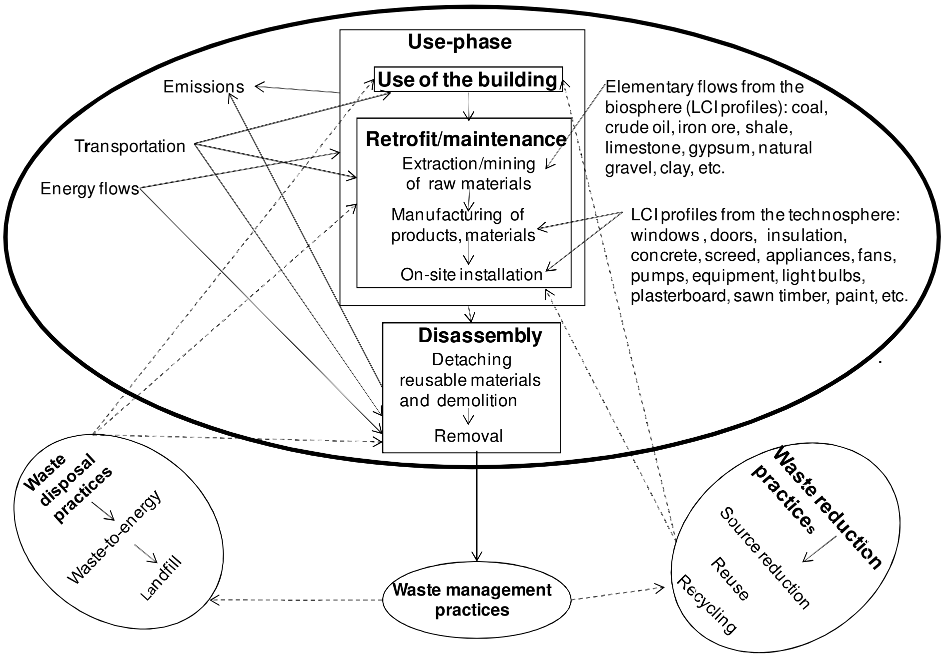

Figure 4.8: Study house system boundary

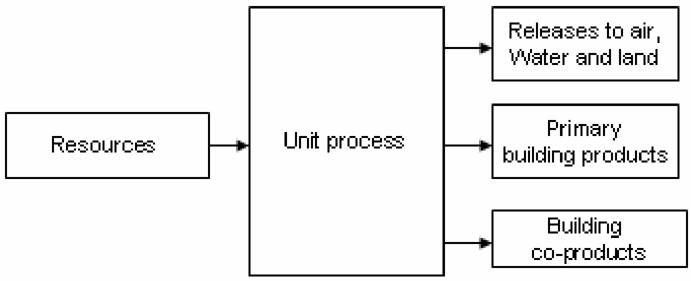

Figure 4.9: Example of a unit process within a building system

Life Cycle Inventory (LCI)

Life cycle inventory analysis (LCI) is the second stage of an LCA (ISO 14040:2006). Life cycle analysis is composed of inputs and outputs in the form of environmental exchanges to and from the building with regard to the building being studied. It involves data collection and calculation procedures to quantify relevant inputs and outputs of a building product system.

A generic parameterized building model was developed in the software GaBi 4.4 (LBP & PE, 2007) in order to simplify the handling of the extended quantity of data and maintain consistency during the assessment of all representative archetype houses. The use of generic models in GaBi 4.4 software tool permits the efficient adaptation of the model to contrasting representative archetype houses by parameterising key variables, such as mass or energy fluxes (Nemry et al, 2010). In this respect and based on mass, all representative archetype houses to be evaluated shared a common arrangement within the GaBi 4.4 scenario parameter explorer. Further details are provided in Section 2.4.1 of Chapter 2 on the application of GaBi software tool.

Service life of products and of complete buildings

Like complete buildings, service life assumptions for building materials are required in order to evaluate the energy and environmental impacts of the buildings. The service lives of manufactured materials, products and equipment have been assumed based on manufacturers' information, literature and examples from previous renovation projects- many of such examples are in Energy Saving Trust (EST, 2007, 2010). Table 4.1 illustrates life expectancy of the construction materials and components used in the study. Similarly, Table 4.2 illustrates house material component replacement rates for maximum service life. The data have been considered appropriate as most of them are based on past practical projects and previous studies on upgrade projects.

Table 4.1: The life expectancy of construction materials and components

	Material and component	Life expectancy in years	Reference	Comment
1	Windows and doors	40+	EST, (2005)	
2	Roof coverings	60+	EST, (2005)	Contingent upon installation this element is expected to last the life of the building
3	Paint, internal	7	EIMA, (2009)	
4	Paint, exterior	10	EIMA, (2009)	
5	White goods (i.e. large appliances)	12	SABO, (1992)	
6	Brown goods	3		Assumption is based on experience and products brochure
7	Insulation, joist, internal walls	50	SABO, (1992)	Internal wall was assumed for plasterboard
8	External concrete block walls	60+	EST, (2005)	Element is expected to last the life of the building
9	Foundations	60+	EST, (2005)	
10	Water pipes and electric wires	50	SABO, (1992)	Element is expected to last the life of the building
11	Manufactured fireplace	50	Medgar L. et al., (2008)	Element is expected to last the life of the building
12	Boiler	16	SABO, (1992)	
13	Wood-fuelled heating appliance	20	EST, (2007)	
14	Photovoltaic panel	30		Manufacturers' brochure
15	Solar thermal system	25	EST, (2005), CIBSE	
16	Scroll compressors to GSHP	25	EST, 2007	Daikin+ other
	Polyethylene pipe ground looping to GSHP	50	EST, 2007	
17	Light bulbs	2		Based on experience
18	MVHR	20	EST, (2005)	
19	Water pump	20		Based on experience

For a given building the number of replacements of the individual building materials were then determined based on its residual service life. The number of material replacements is determined as follows (Adalberth, 1997):

$$\frac{\text{Residual service life of the building}}{\text{life span of material}} - 1$$

Where, -1 in the formula represents first installation at construction of the building.

Table 4.2: House material component replacement rates for maximum service life

	Material/product	Replacement frequency
		50years-service life
1	Internal paint	4
2	External paint	6
3	MVHR	2 (n/a)
4	Conventional/condensing boiler	2*
5	PV system	1
6	Solar plate	1 (n/a)
7	Water pump	2
8	GSHP and ashp compressors	1
9	Solar thermal system	1

Parenthesis indicates material/product is not part of the package for the no-intervention option; *indicates material/product is not part of the package for the passive house standard option.

Several sources of data

In this section several data sources used in performing the analysis are discussed. It involves compilation of both process analysis and input-output analysis data. Table 4.3 illustrates the combination of several data sources used in this study. Similarly, Table 4.4 illustrates Sources of additional data.

Process analysis data

Overall, process analysis data incorporates data on the physical flows of all processes that are related to the production, consumption and disassembly phases of the house in question. The Energy Performance Survey of Irish Housing (EPSIH) provides the life cycle inventories of construction materials and energy as well as of transportation processes. Similarly, Background datasets are European averages as provided within the GaBi 4.4 software tool including other databases such the European Life Cycle Database, and Plastics Europe.

Table 4.3: Combination of different sources of data according to life cycle phases

		Sources of data	
life cycle phase	Unit process	Process analysis	Input-output analysis
Maintenance	Production of materials of maintenance	Parameter inputs from housing database; background datasets from GaBi software tool	Cost of labour, profit, overhead, etc from Spon's Irish Construction Price Book (Spon, 2008) and Spon's Mechanical and Electrical Price Book, (Spon, 2011
	Transportation	Assumed distances from recyclers; GaBi software transport dataset	Cost of transportation from a previous study
Retrofit	Production of materials of retrofitting	Assumed distances from recyclers; GaBi software transport dataset	• Cost materials of retrofitting from Spon's Irish Construction Book, • Cost of transportation from a previous study
Operational (use) phase	Operation of the building based on use of electricity and household purchased heat energy for space and water heating	• Statistical records of household purchased heat energy and electricity • Gabi energy and emissions intensities	• Fuel cost data from Irish Bordgais
Disassembly	Demolition of the building	• Estimated materials quantities of disassembly • Data on energy for crane lifting from Adalberth et al (2001)	• Transportation fuel costs • Cost of labour for loading and offloading

Other process analysis data were taken from a previous study (Acquaye, 2010). These include percentage shares of national arising embodied CO_2-eq intensity and international arising embodied CO_2-eq intensity of Irish construction, representing 12% and 84%, respectively. The author derived these intensities by applying national emission factors to convert embodied energy intensities of Irish construction to embodied CO_2-eq intensities. The source of energy for crane lifting is further discussed in the section next sections under life cycle inventories.

Table 4.4: Sources of additional data

	Building product	Reference
1	Copper	Deutsches Kupferinstitut, Life Cycle Centre
2	Steel	http://www.worldsteel.org
3	Radiators	http://www.inspiredheating.co.uk/acatalog/Heatrae_Megaflo_Direct_Unvented_Hot_Water_Cylinder.html
4	Boiler-Potterton Promax FSB 30 HE	http://www.energysavingtrust.org.uk/Compare-and-buy-products/Heating/Gas-boilers/Potterton-Promax-FSB-30-HE
5	Solar hot water system	www.csgsolar.com
6	Air Source Heat Pump	www.altherma.co.uk
7	Biomass boilers, burners and stoves	http://www.treco.co.uk/tatano/
8	DHW pump	Combi-Cat Model CC-1
9	DHW cylinder	Ariston. www.centralheating.co.uk
10	VENTOS 50 DC Stand-alone comfort ventilation (MVHR) unit	www.paul-lueftung.net
11	Photovoltaic Cells	1) http://www.solartubecompany.co.uk/photovoltaic-cells/ 2) Solar Module: http://www.gzrichsum.com/webs/solar-module-01.htm
12	DHW Solar cylinder	Kingspan cylinder - Technical specifications Indirect solar Applications using Tribune HE Solar Units

Data gaps: The international impacts induced by the provision of workman's clothing, transportation vehicle and insurance were not calculated due to a lack of data. Such omitted inputs include costs, and energy and emissions intensities of the processes involved in their provision. Even in cases when these inputs are known, it is likely to become intractable to quantify the proportion of those that are attributable to this study as some of the materials and products are expected to be reused on several other sites that are not related to the building in question. However, these data gaps are not expected to lead to any significant error in the analysis.

Energy and LCA tools used in the study

The annual house operational energy use for heating, lighting, ventilation and appliances was modelled using EDEM/HEM energy modelling tool (See Section 2.4.1 of Chapter 2 – review of literature). Similarly, the impacts attributable to the representative archetypes' across life cycle phases (including the outputs of EDEM/HEM for the operation of the building) were evaluated using the GaBi 4.4 LCA tool (See also Section 2.4.1 of Chapter 2 – review of literature).

Life cycle inventories (process analysis)

Using the detailed technical descriptions for each archetype, and other life cycle inventory data from the EPSIH, life cycle inventories for the refurbishment work were generated. Residual building service lives and the life expectancy of the products/materials were also used in this process. The rate of replacement yields the number of replacements of products (e.g. replacing PV system every 30 years) and number of upgrade actions (e.g. internal and external redecorations every 7 and 10 years, respectively) for each construction detail over the residual life of the building. However, for the purposes of generating mass of materials quantities to be transported to recyclers (as pre-use phase of the building is outside the scope of this study) at disassembly, a list of materials quantities was generated for archetype one for the BaseCase scenario. This resulted in the total mass of materials for transportation at disassembly. Since envelope construction (i.e. concrete roof, solid floor and masonry wall) is similar for all archetypes and represents the bulk of the mass for transportation, the mass of materials for transportation for each of the remaining archetypes was then calculated based on the mass per m^2 derived from archetype one. The procedure was also repeated for all retrofit options. Tables of mass of house materials list for archetype

1 across all house options are presented in Appendix 3. The weights (kg) of these materials are then weighted to obtain those of the remaining archetypes.

On the basis of the study house system boundary, four life cycle phases were considered. These include operation, retrofitting, maintenance and disassembly phases. The construction phase burdens were not considered as the emissions from the phase are considered 'sunk' emissions as these have already been incurred and cannot be recovered. The impacts induced by fixing of retrofitting materials and products during renovation and maintenance was also excluded from this present section but accounted for in the section under input-output analysis as these represent processes for which only I-O data are available.

The life cycle inventories for each life cycle phase considered are described below.

a) Maintenance phase

On the basis of the study house system boundary, the maintenance phase in the building's life cycle encompasses all activities required to produce all materials, products and components required for replacement at the end of their service lives. A complete list of maintenance materials is included in the bill of materials quantities prepared for this study.

Material production for the maintenance phase includes burdens (embodied primary energy and related emissions) from material extraction, refinement, processing and manufacture of materials, products and components including all associated transportation to site (see Table 4.7 above).

b) Retrofit phase

The retrofit phase in the building's life cycle encompasses all activities required in the application of energy saving components to the building. A complete list of materials due to retrofit of the building is included in the bill of materials quantities prepared for this study.

Material production for retrofit phase includes burdens from material extraction, refinement, processing and manufacture of materials, products and components including all associated transportation to site.

c) Operation phase

Operation phase of the building includes energy and burdens from households' use of heat energy and electricity for space and water heating, lighting and appliances. It also includes energy and burdens from transportation of purchased thermal heat (e.g. oil) from suppliers to the building site. The impacts of the operation phase have been calculated as a function of fuel use. The energy requirements during the operational phase were calculated using the HEM energy modelling software tool. It calculates annual energy requirements for space heating, water heating, ventilation and electricity.

Factors taken into consideration include: fabric inputs (U-values of the construction details, thermal bridges, air leakage, window size, exposure, shape, floor area, capacity, and capacity position); system inputs(system fuel, heating system type, hot water system type, controls, lights, ventilation/cooling and renewables); and demand-related inputs (climate, heating demand, hot water demand, appliances and grid CO_2 intensity).

d) Demolition of the building

Demolition of the building includes energy and burdens from the conversion of energy used for removing recyclable materials and their transportation as well as the actual demolition of the buildings. This energy is mainly energy use due to crane lifting, excavation, the removal of ground floor slabs, and leveling the site. The energy used for these processes was calculated using data collected by the Danish Research Institute (Andersen et al, 1993). The authors found this energy to be 2kWh/m^2 for crane lifting; 3kWh/m^3 for excavation and removal of ground floor concrete slab; and 3kWh/ton for smoothing of soil, respectively. The phase also includes burdens from the production and consumption of fuels used for transporting all waste.

Transportation assumptions

This present study assumes there is a recycler nearby the building at approximately 50km. It should be noted that the supplier of the new products during maintenance are expected to transport all waste materials to a recyclers where they will be sorted and sent for reuse or recycling or energy recovery or landfill. The transport dataset from GaBi 4.4 already accounts for the transportation of fuels from the point of extraction/mining to the manufacturing centre of the required finished products. However, transportation burdens from the mainstream and downstream sectors are also based on the transportation dataset from GaBi 4.4 and are modelled based on an assumed distance of 50 km from suppliers to the building site, and of waste from building site to recycler.

Other omitted processes

Inventories of some processes and features were excluded from the house system boundary due to insignificant application. These include white and brown goods, especially since these can be separated from the building and are not fixed. This study was therefore limited to the building elements, heating system, and electrical system.

Energy sources

In the calculation of environmental impacts, it is assumed that the energy supply system will be constant during the entire lifetime of the building. The current Irish electricity grid mix has been used to evaluate the environmental impact induced by electricity production for all buildings. Similarly, environmental impacts from heat production were calculated using Irish fuel parameters for natural gas and oil and based on GaBi energy and emissions intensities.

4.3.2 Input-output LCA methodology

This section discusses the detailed methodology used in calculating the energy and emissions attributable to services.

Input-output data

Input-output data includes all monetary flow data across retrofit, maintenance and disassembly phases. Data on costs of materials, products, labour, profits and overheads were obtained from the Spon's Irish construction price book (2008) and Spon's Mechanical and Electrical Price Book, (Spon, 2011). The Price books also provide additional information on plant hire and other services. Data on fuel prices were obtained from Finfacts (2012), an Irish business-news portal and Bordgais, an Irish government subsidiary responsible gas and electricity supply in Ireland. Other sources of data regarding transportation and crane hire were obtained from Building Journal (2012). All costs as obtained from the different sources were then adjusted to 2005 base year of study. A table of bill of quantities for each archetype for all scenarios indicating all prices is provided in Appendix 5.

Other input-output data was taken from a previous Irish study, Acquaye (2010). The data can be categorised into two groups based on estimated sub-sector embodied energy intensities of Irish construction along five construction sub-sectors to be: 0.0569, 0.2122, 0.1164, 0.1794 and 1.2769kWh/€ for ‘Ground Works’, ‘Structural Work’, ‘Services’, ‘Finishes’ and ‘Plant Operation’, respectively; and the corresponding estimated sub-sector energy-related CO_2-eq intensities for these sections to be: 0.139, 0.055, 0.031, 0.004, and 0.337kgCO_2-eq/€. Table 4.5 below shows the summary of this data.

Table 4.5 Sub-sector embodied energy/emissions intensities of Irish construction

		sub-sector embodied energy intensities of Irish construction (kWh/€)	Sub-sector energy-related CO_2-eq intensities of Irish construction (kgCO_2-eq/€.)	Source of data
1	Ground works	0.0569	0.139	An Irish study, Acquaye 2010
2	Structural work	0.2122	0.055	
3	Services	0.1164	0.031	
4	Finishes	0.1794	0.004	
5	Plant Operation	1.2769	0.337	

The calculation of these intensities was based on the 2005 baseline year (the most recent year in which the Central Statistics Office has published Supply and Use Input-Output Tables for Ireland.

Life cycle inventories (input-output analysis)

The following sources provided data for the generation of life cycle inventories in the form of a bill of materials quantities (See Appendix 5) of the needed costs of services for the refurbishment work: detailed technical descriptions of representative archetype houses (see Tables 5.2a and 5.2b in Chapter 5 for summary of the retrofit measures and archetype description), ‘Background data’ from the EPSIH, Spon’s Irish Construction Price Book (2008) and Spon’s Mechanical and Electrical Price Book. The process proceeded as follows. The bill of material quantities of a representative archetype for each dwelling type was generated for each scenario. Since retrofit measures are similar for all archetypes within a given dwelling type and a given scenario, bills of quantities for the remaining archetypes within each dwelling type for each scenario were then generated using the respective material quantities and the corresponding unit costs. The bill of material quantities of each representative archetype for a given dwelling type for each scenario is presented in Appendix 5.

4.3.3 Calculation of the BaseCase hybrid energy/emissions

The hybrid energy/emissions comprise process analysis energy/emissions and input-output (I-O) analysis energy/emissions. Then, for a given life cycle phase, the hybrid energy/emissions is the summation of the process analysis energy/emissions and the I-O energy/emissions. Figure 4.10 illustrates the hybrid analysis technique. Using each box in Figure 4.10, the calculation will proceed as follows. First, on the basis of the characteristics of the developed archetypes, a bill of quantities of materials and costs was prepared for each of the archetypes for all house scenarios.

Second, using the characteristics of the archetype, its annual operational energy (kWh/m^2) use for heating and electricity was obtained as outputs from EDEM/HEM energy tool (item number one in the red in Figure 4.10 refers). The EDEM/HEM heating energy out-puts were converted into Kg/yr of purchased heat energy (PHE) and then used as input data into the GaBi 4.4. Similarly, the EDEM/HEM outputs for house electricity usage were converted from kWh/m^2/yr into kWh/yr and fed directly into the GaBi 4.4. The GaBi internal processors automatically apply GaBi energy/emissions intensities and calculate the life cycle impacts associated with the operational energy use of the archetype house. For example, using eQuest, a DOE2 interface, Scheuer et al

(2003) evaluated operational phase annual energy based on the characteristics of the building such as use and occupancy patterns of the building spaces, the architectural and mechanical features. Nemry et al. (2010) developed a model of the building stock for the EU-25. The zonal heating degree days (HDD) for each building type were converted into kWh and used as inputs into GaBi 4 to evaluate the environmental impacts attributable to heating. The above examples support the use of energy software to calculate annual operational energy used in this thesis. Similarly, the work of Nemry et al. (2010) supports the use of LCA to calculate environmental impacts attributable to house operational energy.

While a distinction was made between the different fuel types used in the study (e.g. oil, gas and electricity), operation phase energy predictions from the Gabi software tool for the unit archetype in question were then separated into: 1) energy/emissions due to international sources (imported) fuel supply and production for the unit archetype. This portion was treated as international since little or no fossil fuel production occurs in Ireland; and 2) energy/emissions due to the unit archetype Irish feedstock heat energy/emissions and electricity requirements/emissions. This portion was treated as national since Irish fuel mix for electricity generation has been over the years predominantly fossil fuels. For example, in 1990, 2005 and 2008, the fossil fuel shares of electricity generation fuel mix represent 98.1% (SEI 2009), approximately 96% (SEI 2006) and 92.9% (SEAI 2009), respectively and little or non of these are produced in Ireland (SEAI, 2009). However, a search through the literature does not reveal any previous studies that used a similar method to separate energy/emission into international and national sources.

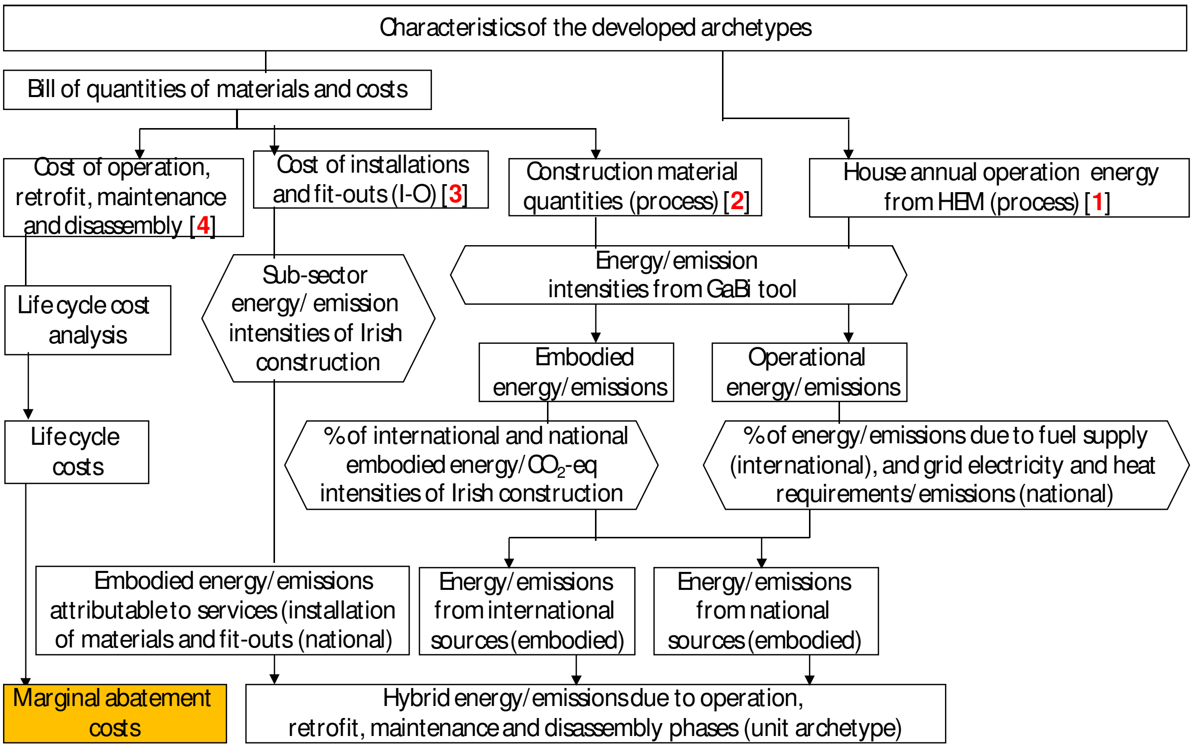

Figure 4.10 – Study hybrid analysis model

Third, construction materials quantities (mass in kg) from the bill of quantities were fed as input data into GaBi 4.4. Similarly, the internal processor applied GaBi 4.4 embodied energy/emissions and calculated the embodied energy/emissions attributable to retrofitting, maintenance and disassembly phase. Using the share % of international and national embodied energy/CO_2-eq intensities of Irish construction, these were separated along international and national sources of energy/emissions. Nemry et al. (2010) developed a model of the building stock for the EU-25. They used European average datasets background datasets in GaBi 4 to evaluate embodied impacts associated with the buildings. This technique is found appropriate for use in this thesis, especially as the results can be separated along international and national sources.

Fourth, on the basis of the bill of quantities that was prepared for the refurbishment work, the sub-sector costs to which only I-O analysis can be applied were obtained from the bill of quantities. Then every entry in terms of Euro was classified into one of the sub-sectors of Irish construction (with units in kWh/Euro) (i.e. ground works, structural works, services, finishes and plants operations). Zero was recorded for those sub-sectors that are not related to refurbishment (e.g. zero was recorded for structural works since it was a retrofit project - see section on I-O data sources). For example, cost of finishes (e.g. painting) was classified under the maintenance phase. The input-output total energy/emissions due to refurbishment services of the unit archetype in question were then derived as the sum of the respective products. These energy estimates were considered national since all refurbishment services occur in Ireland.

The input-out energy/emissions of a given life cycle phase was then derived as the product of the input-output energy/emissions prediction of the unit archetype in question and the cost of refurbishment services of the given life cycle phase divided by the total cost of refurbishment services of the unit archetype. However, a search through the literature does not reveal any previous studies that used a similar method to evaluate energy and emissions attributable to I-O data.

Fifth, and finally, given by the above explanations and based on Figure 4.10, the total hybrid life cycle energy requirement/emissions of the unit archetype represent the sum of the international arising and national arising energy requirements/emissions across life cycle phases.

The equations representing the calculation of these energy requirements/emissions are derived and given below.

Process embodied energy/emissions

The process embodied energy requirements/emissions across maintenance, retrofit and disassembly phases can be represented by equation 4.1.

$$E_{pro-emb-\text{int}-lcp,i} = E_{pro-emb-tot-lcp,i} * I_{emb} \quad \text{(Equation 4.1)}$$

$E_{pro\text{-}emb\text{-}int\text{-}lcp}$, $_i$ = international process embodied energy/emissions due to material production for the unit archetype, *i* and for the corresponding life cycle phase.

$E_{pro\text{-}emb\text{-}tot\text{-}lcp}$, $_i$ = Total process energy predictions for the unit archetype *i* and, for the corresponding life cycle phase (calculated using GaBi).

I_{emb} = shares (%) of international arising embodied energy/emissions intensity of Irish construction (Acquaye, 2010).

Then the national process embodied energy/emissions of the corresponding life cycle phase of the unit archetype, *i* were also calculated as the difference between the GaBi energy predictions and that of the international sources, using equation 4.2.

$$E_{pro-emb-dom-lcp,i} = E_{pro-emb-tot-lcp,i} - E_{pro-emb-\text{int}-lcp,i} \quad \text{(Equation 4.2)}$$

The process embodied energy requirement/emissions across maintenance, retrofit and disassembly of the unit archetype is the sum of the equations 4.1 and 4.2.

Operational phase process energy/emissions

The process international operational heat/emissions due to fuel supply and production that occurred abroad for heat energy usage of the unit archetype were calculated using equation 4.3.

$$E_{pro-ops-\text{int}\,heat-lcp,i} = E_{pro-ops-totheat-lcp,i} * I_{ops-\text{int}\,heat} \quad \text{(Equation 4.3)}$$

$E_{pro\text{-}ops\text{-}intheat\text{-}lcp}$, $_i$ = international process operational heat energy/emissions due to fuel supply and production that occurred abroad for the unit archetype *i* heat usage.

$E_{pro\text{-}ops\text{-}totheat\text{-}lcp}$, $_i$ = Total process heat requirement/emissions predictions for the unit archetype *i* (calculated using GaBi).

$I_{ops-intheat}$ = shares (%) of heat/emissions due to fuel supply and production that occurred abroad for the unit archetype *i* heat usage.

Then the corresponding heat/emissions from national sources were calculated using equation 4.4.

$$E_{pro-ops-domheat-lcp,i} = E_{pro-ops-totheat-lcp,i} - E_{pro-ops-\mathrm{int}\,heat-lcp,i} \quad \text{(Equation 4.4)}$$

$E_{pro\text{-}ops\text{-}domheat\text{-}lcp,\ i}$ = national process operational feedstock energy/emissions that occurred in Ireland for the unit archetype *i* heat usage.

The process international operational electricity/emissions due to fuel supply and production that occurred abroad for the Irish grid electricity generation fuel mix for the unit archetype were calculated using equation 4.5.

$$E_{pro-ops-\mathrm{int}\,elec-lcp,i} = E_{pro-ops-totelec-lcp,i} * I_{ops-\mathrm{int}\,heat} \quad \text{(Equation 4.5)}$$

$E_{pro\text{-}ops\text{-}totelec\text{-}lcp,\ i}$ = Total process operational electricity/emissions predictions for the unit archetype, *i* (calculated using GaBi).

Then the corresponding electricity requirement/emissions from national sources were calculated using equation 4.6.

$$E_{pro-ops-domelec-lcp,i} = E_{pro-ops-totelec-lcp,i} - E_{pro-ops-\mathrm{int}\,elec-\mathrm{int}-lcp,i} \quad \text{(Equation 4.6)}$$

$E_{pro\text{-}ops\text{-}domelec\text{-}lcp,\ i}$ = national process operational electricity/emissions due to grid electricity generation that occurred in Ireland and supplied to the unit archetype *i* electricity usage.

Input-output energy/emissions

Similarly, given the above explanations, the input-output energy requirement/emissions for the refurbishment services of a unit archetype, i can be represented by equation 4.7 below.

$$E_{I-O-tot,i} = \sum_{j=1}^{5} (EI_j * C_{j,i}) \qquad \text{(Equation 4.7)}$$

$E_{I\text{-}O\text{-}tot,\,i}$ = Total input-output energy/emissions prediction for the refurbishment services of the unit archetype, *i*.

EI_j = sub-sector embodied energy/emissions intensity of the five Irish construction sub-sectors (j) of Irish construction (kWh/€).

$C_{j,\,i}$ = I-O costs of refurbishment services for archetype *i*, classified by Irish construction sub-sector j (€).

The input-out energy requirement/emissions of a given life cycle phase of the unit archetype, i can be represented by equation 4.8 below:

$$E_{I-O-lcp,i} = E_{I-O-tot,i} * \frac{C_{lcp,i}}{C_{tot,i}} \qquad \text{(Equation 4.8)}$$

$C_{lcp,\,i}$ = cost of refurbishment services for a given life cycle phase of a unit archetype, *i*.

$C_{l,\,i}$ = total cost of refurbishment services of archetype, *i*.

Hybrid life cycle energy requirement/emissions

Given by the above equations, the hybrid result is some combinations of the process analysis and input-output analysis results. Thus, the hybrid energy requirement/emissions of a unit archetype, i is the sum of the equations 4.1, 4.2, 4.3, 4.4, 4.5, 4.6 and 4.8. This can be represented by equation 4.9 below:

$$E_{hybrid-lc,i} = Eq\,4.1 + Eq\,4.2 + Eq\,4.3 + Eq\,4.4 + Eq\,4.5 + Eq\,4.6 + Eq\,4.8 \qquad \text{(Equation 4.9)}$$

$E_{hybrid-lc,\,i}$ = hybrid energy requirement/emissions of a unit archetype, i

Eq = Equation

Hybrid energy requirement/emissions at population levels

The hybrid energy requirements/emissions of a population at average dwelling and national housing stock levels were calculated by scaling up the respective individual archetype energy requirement/emissions.

The hybrid energy requirement of the population at archetype average dwelling level were calculated as the sum of the product of the hybrid energy requirement/emissions of the unit archetype and the corresponding number of houses for which it is representative in Irish housing divided by the total number of houses in Irish housing stock. This can be represented by equation 4.10 below.

$$E_{hybrid-tot-lc,avg} = \frac{\sum_{i=1}^{n} E_{hybrid-lc,i} * N_i}{\sum_{i=1}^{n} N_i} \qquad \text{(Equation 4.10)}$$

$E_{hybrid-lc,\,i}$ = hybrid life cycle energy requirement/emissions of the unit archetype.

N_i = the total number of dwellings in Irish housing stock for which archetype, *i* is representative.

n = number of archetypes.

i = archetype.

The hybrid energy requirement/emissions at national housing stock level were calculated as the sum of the product of the hybrid life cycle energy requirement/emissions of the unit archetype and the corresponding number of houses for which it is representative in Irish housing. This can be represented by equation 4.11 below.

$$E_{hybrid-tot-lc,stock} = \sum_{i=1}^{n} E_{hybrid-lc,i} * N_i \qquad \text{(Equation 4.11)}$$

The hybrid energy requirement/emissions at national housing stock level during a lifetime of the unit archetype were calculated as the product of the national housing stock life cycle hybrid energy requirement/emissions and the service life of the unit archetype. This can be represented by equation 4.12 below.

$$E_{hybrid-stock,lifetime} = \sum_{i=1}^{n} E_{hybrid-tot-lc,stock} * g \qquad \text{(Equation 4.12)}$$

g = 50 years.

4.3.4 Retrofit measures to Base-Case dwellings and cost assessment of the retrofit scenarios

In Section 4.3 above, a life cycle assessment of the energy required and associated environmental impacts as a result of retrofitting the existing Irish housing stock were performed. While a summary of the various retrofit measures that can be applied to Irish housing has been discussed in Chapter Three, this section presents specific descriptions of the various energy improvement measures that can be applied to the Base-case representative archetype houses to achieve the selected retrofit scenarios. Next, cost assessment of the various house scenarios is presented.

Retrofit measures applied to BaseCase dwellings

The available retrofit measures include those specified in the current 2010 Irish building regulations, and those identified for the passive house option. They include those that are within the contemporary obtainable practices, and in particular the examples of feasible retrofits identified from Energy Saving Trust publications (EST, 2007 and 2010). These studies focus on both low and zero-emissions technologies that are expected to be technically feasible and currently available to achieve CO_2 emissions reductions. However, care was also taken to distinguish between retrofit measures regarding the level of environmental performance and technical suitability. There are cases when options with higher environmental performance exist but may at the same time be technically less practicable or too expensive (Nemry, 2010). External insulation is an alternative to internal insulation, especially as it results in avoided internal space encroachment for smaller rooms. Moreover, external insulation will drastically change the appearance of a building and planning permission may be required (EST, 2006). Similarly, mineral wool (slab) internal insulation backed dry-lining is both economically and environmentally preferred to insulation-backed plasterboard (e.g. expanded polystyrene). This is because expanded polystyrene insulation which belongs to the group of insulation made from polymers has a higher embodied energy of production and a higher cost per m^2.

For the buildings, the thermal performance can be improved by increased envelope insulation, reduced air permeability, improved ventilation systems and application of both low to zero-emissions heating technologies. By way of example, the retrofit measures chosen for Archetype 1 to bring it up to Current and Passive House standards is given in Table 4.6 below. Similarly, Table 4.7 shows the description of the representative variables complementing Table 4.6. The remaining archetype upgrades are detailed in Appendix 4. Moreover, Table 5.2b in Chapter 5 further provides a summary of the retrofit measures applied to all archetypes and is linked to the summarised description of the archetypes.

Retrofit measures within the current standard scenario

Within the Current Regulations scenario, retrofit measures that have been provided include those that are contained in the current building regulations.

1. *Fabric upgrades:*

- Since cavity walls already attained a U-value of $0.5W/m^2K$ which is below the requirement of the current building regulations, they were improved to achieve a U value of $0.21W/m^2K$ by increasing mineral wool insulation (slab) from 75 to 180mm and using 12.5mm plasterboards fixed on 38mm timber studs at 400mm centres. The weight of additional insulation required was calculated as the product of the area of wall, insulation thickness and density of insulation.
- The pitched roof (ceiling insulation) U-values were reduced from 0.33 to 0.16 W/m^2K by increasing mineral wool insulation (quilt) from 135 to 270mm (first layer between joists, second layer across the joists).
- The ground floor U-value was improved from 0.5 to $0.21W/m^2K$ by increasing polyurethane rigid foam insulation from 50 to 120mm lay on a new concrete slab topped off with a 75mm screed and includes 25mm polyurethane rigid foam insulation up-stand to minimize thermal bridging at the junction of the floor and the wall.
- As air leakage through the seal has the greatest impact on window heat loss, existing double glazed windows were replaced with factory triple-glazed window

with a low-emissivity coating, and 2 gaps with air, to achieve a U-value of $1.6W/m^2K$.

- The dwelling was improved to have air change rate based on 2010 detail i.e. 0.35ac/h at 50Pa by reducing the existing air change rate from 0.87ac/h to 0.35ac/h. This was achieved by sealing cracks and small gaps in the external fabric that are not designed in, such as spaces between window frames and external walls and small gaps around penetrations through the external envelope. All of these effectively reduce significantly the basic air change rate induced by type of construction, e.g. masonry.

2. *Heating systems to current standards:*

- In addition to fabric upgrades, existing heating systems such as gas, oil, electric and solid fuel heating systems are upgraded to condensing, instantaneous water heating boiler (90% seasonal efficiency) plus advanced controls for heating systems.
- The existing lagging jacket to domestic hot water cylinder (DHW) was changed to factory PU-foam having zero ozone potential and a minimum density of $30kg/m^3$ and increased thickness from 30mm to the full recommended thickness of 50mm.
- The dwelling was provided with a solar hot water system having a $4m^2$ flat plate system and a solar hot water cylinder.

Table 4.6: Detailed description of the retrofit measures relative to the No-intervention house option

Archetype 1				
		Base-case scenario	**Current standard scenario**	**Passive House standard scenario**
Materials	**Building element**	**Existing information as above**	**Derivation of new retrofit measures relative to the No-intervention option**	
Mineral wool (slab)	Wall insulation	75(mm, thick)	427 kg	829 kg
Mineral wool (quilt)	Roof insulation	135 (mm, thick)	186 kg	366 kg
Polyurethane rigid foam insulation	Ground floor	50 (mm, thick)	279 kg	559 kg
Polyurethane rigid foam insulation	DHW cylinder insulation	30* (mm, thick)	1.2 kg	3kg
Polyurethane rigid foam insulation	Door insulation	0	3.53 kg	3 kg
Sealant	Air change rate	0.87 ac/h	0.35 ac/h	0.25 ac/h
UPVC and glass	Windows	Double-glazing	Triple-glazing (1 low-emissivity coating, 2 gaps with air to achieve a U-value of 1.6.)	Triple-glazing (1 low-emissivity coating, 2 gaps with argon gas, and integral draught proofing/stripping, to achieve a U-value of 0.8 (Gustavsson, 2010))
Not available	H/system	Conventional oil boiler	Condensing/boiler, Solar hot water - 4m^2 solar flat plate system	Ground source heat pump (Gshp), Solar hot water - 4m^2 solar flat plate system, Mechanical ventilation plus heat recovery (MVHR) and PV system

*DHW cylinder lagging jacket

Table 4.7: Description of representative variables complementing Table 4.7

Variable and unit	**Quantity**
Wall area (m^2)	161
Roof area (m^2)	115
Floor area (m^2)	133
DHW insulation area (m^2)	2
Density of mineral wool (slab) (kg/m^3)	25
Density of mineral wool (quilt) (kg/m^3)	12
Density polyurethane rigid foam insulation (kg/m^3)	30
Window size (m^2)	30

Passive upgrade measures

In order to meet passive house standards, higher levels of retrofit measures had to be provided than for the current standards. These measures include those within the zero-emissions-solutions.

1. *Fabric upgrades from current standard to passive house standard.*

- Since cavity walls already attained a U-value of $0.21W/m^2K$ in compliance with the requirement of the current building regulations, glass wool (slab) insulation to internal dry-lining was increased from 180mm to 280mm to achieve a U-value of $0.12W/m^2K$ to comply with the passive house standards. The weight of additional insulation required was calculated as the product of the area of wall, insulation thickness and density of insulation. However, it assumed that the rooms are large enough to accommodate the space requirements for the additional insulation without necessarily resulting in room space reductions.
- The pitched roof (insulation at ceiling level) U-value was improved to $0.1W/m^2K$ by increasing glass wool insulation from 270mm to 400mm.
- In addition to current standards, existing windows were further replaced with high performance triple-glazed windows that incorporate integral draught stripping, to achieve a U-value of 0.8 (Gustavsson and Joelsson, 2010).
- The ground floor U-value was improved from the current standards requirement of 0.21 to 0.1 W/m^2K or less by increasing polyurethane rigid foam insulation 120mm to 190mm.
- The dwelling was improved to have tight infiltration by reducing air change rate from 0.35ac/h to 0.25ac/h or less. This was achieved based on: properties with high

performance windows that incorporate integral draught stripping; and substitution of the existing flues, vents, fans, etc with MVHR (details are provided below).

2. *Heating systems to passive house standards: these include -*

- In addition to fabric upgrades to passive house standards, existing condensing, instantaneous water heating boiler was substituted with ground source heat pump including the provision of advanced controls for heating systems. However, since heat pumps heat water to a lower temperature compared to traditional boilers, it is assumed that the existing radiators are large enough to provide the same level of heat required.
- A whole dwelling super performance mechanical ventilation system and heat recovery (MVHR), including passive flue gas heat recovery device (i.e. 88% heat recovery and 0.6W/l/s specific fan power). The electric resistance heating in the supply air of the (MVHR) provided additional space heating.
- The 50mm factory-PU-foam insulation to domestic hot water cylinder (DHW) was increased to 75mm. it should be noted that the cylinders from the previous upgrade are expected to serve as stand-by for additional supply.
- The dwelling was provided with solar hot water system comprising three solar collectors of $4m^2$ per unit to provide the energy for approximately 40% of the hot water demand and a PV generation system comprising $8m^2$ mono-crystal panels comprising of an array of four panels at approximately $2.0m^2$ per panel. It should be noted that the solar hot water pump was designed to be powered by solar PV, and the above useful energy from solar collectors was net, as the energy used in powering (75kWh/yr) was deducted from the total output from solar PV.

4.3.5 New environmental profile of the retrofitted dwellings

In Section 4.3, a life cycle assessment of the environmental impacts associated with the Base-case Irish housing under no-intervention option was performed based on the developed 13 archetypes. Subsequently, in Section 4.4, suitable retrofit measures to improve the environmental performance of the dwellings were identified. In this section, the process of calculating the new environmental profile of the retrofitted dwelling under Current Regulations and Passive House standard scenarios is discussed.

On the basis of the methodology in Section 4.3.3, the process for calculating the new environmental profile of the retrofitted dwelling is as follows. First, for each of the 13 archetypes, the generic parameterised model earlier developed in GaBi was adjusted with the equivalent parameter input (see Section 4.3 above under 'Building system and system boundary') to evaluate the new environmental profile of the retrofitted building under Current Regulations and Passive House standard scenarios. It should also be noted that these parameter inputs include those for the number of replacement products and components based on the service life of the building. Second, the procedures for calculating environmental impacts in Section 4.3 were then repeated in succession for all archetypes under current standard and passive house standard options. The new environmental impacts of the different retrofit options are then first compared to the BaseCase scenario whilst the Current Regulations and Passive House standard scenarios were also compared in Chapter 5 under 'Results and discussion'.

4.4 Cost evaluation of the different house options

In Sections 4.3, 4.4 and 4.5, the procedures for calculating the environmental impacts of the BaseCase scenario, applying suitable retrofit measures for the BaseCase archetypes, and calculating the new environmental impacts of the retrofitted options were discussed.

As economic information serves to balance information on total environmental impacts of the housing stock, this section discusses the cost assessment of the maintenance of the Base-case scenario as well as the cost assessment of the retrofitted options. The assessment methodologies include life cycle cost assessment (LCCA) and Marginal Abatement Cost (MAC).

4.4.1 Sources of data

Like LCA, data is required for the cost evaluation of a project. Life cycle cost analyses for the Base-case building and both retrofit scenarios were performed, using both energy and non-energy cost data from the house bill of materials quantities (See Figure 4.10). It should be noted that non-energy costs of an improvement from BaseCase to other level refer to maintenance, repair and replacement of materials and components over the lifetime of the building.

Fuel quantities for the respective individual representative archetype houses were derived as output from HEM energy modelling software. The operation energy costs for each of the scenarios were calculated as the product of the energy prices and the respective fuel quantities from the HEM energy modelling software. A detailed breakdown of materials and operation costs are in Appendix 4.4.

The methodology used in calculating non-energy costs include a detailed breakdown across life cycle phases by construction materials and products, and assigning costs to each material component or product based on information from Spon’s Irish Price Books (Spon, 2008) and Spon’s Mechanical and Electrical Price Book (Spon, 2011). These prices were adjusted to the 2005 base year of study. The costs include all labour, materials, overheads and profits required to carry out a LCCA for the Base-case and the retrofit scenarios.

4.4.2 Life cycle cost analysis (LCCA)

While life cycles cost analysis has been discussed in detail in Chapter 2, in this section, a detailed LCCA methodology is presented. In an LCCA, the estimation of total costs of building project alternatives can be discounted or non-discounted. The discounted LCC method takes into account first costs, including capital investment costs, purchase, and installation costs; future costs, including energy costs, operating costs, maintenance costs, capital replacement costs, financing costs; and disposal costs, over the service life of the building. In this study, the discounted LCC method involving the calculation of the net present value of a project alternative is used.

Calculation of Net Present Values (NPV) across life cycle phases

The present value (PV) of a project alternative is the cash amount received or paid at a future point in time calculated using a discount rate. Thus, the net present value (NPV) of a project alternative is the summation of all PVs to represent the life cycle cost (LCC) of the project alternative. In this study, a simplified LCC formula for calculating the LCC of an archetype of the house scenario in question is given as follows:

$$LCC = R + M + D + E \qquad \text{(Equation 4.13)}$$

R = present (real) value capital costs of energy savings components.

M = present value capital replacement costs and non-fuel operating, maintenance, and repair costs.

D = present value disposal costs.

E = present value energy costs.

In the remaining part of this section the step by step calculation of NPVs across maintenance, retrofit, operation and disassembly phases is discussed.

The net present value (NPV) of the maintenance phase of an archetype was calculated based on the expenses for regular servicing and replacement of building systems up to their ends of lives. These include both capital replacement of heating and ventilation systems, such as boiler, mechanical ventilation and heat recovery (MVHR) as well as annual replacement of costs of (filters, photovoltaic (PV), compressor for heat pumps and loop circulating pump for ground source heat pump). The phase also incorporates yearly servicing of boiler; and scheduled repainting of the building. In order to evaluate the marginal abatement costs (MAC) for Irish domestic scale PV and SWH, Ayompe (2011) evaluated the NPV of the capital costs, operation and maintenance of the appliances using life cycle cost analysis technique.

In this study, the net present value (NPV) of the maintenance phase is the sum of PVs for all capital replacements of building systems including occasional servicing of appliances, in a given year (n) at a given discount rate (d). The net present value (NPV) of the maintenance phase is represented by equation 4.14 below.

$$N_{vm} = \sum_{n=0}^{k} F_{vm,n} (1+d)^{-n} \qquad \text{(Equation 4.14)}$$

N_{vm} = net present value (NPV) of the maintenance phase.

n = year of occurrence.

k = last year of occurrence.

$F_{vm,n}$ = present value of all capital replacements of building systems including occasional servicing of equipment in year n to last year of occurrence, k.

d = discount rate (%).

n = year of occurrence.

The net present value (NPV) of the retrofit phase was calculated based on the cost of improving the BaseCase scenario to the level of the selected retrofit scenario in question. Using the total quantities of capital applications of materials, components and building systems, the total capital cost of retrofitting was calculated. The base year total cost of retrofit was then applied once as capital cost and discounted to last year of occurrence. The net present value (NPV) of the retrofit phase of a unit archetype of the house scenario in question can be represented by equation 4.15 below.

$$N_{vr} = F_{vr,n}(1+d)^{-n} \qquad \text{(Equation 4.15)}$$

F_{vr} = present retrofit cost discounted to present value in year n (€).

The calculation of the cost of the disassembly phase was based on the cost of detaching reusable materials, demolition of the building, and transporting all these materials to recyclers. Such costs include labour costs for crane lifting, loading, and transportation and fuel costs. The total loading for transport was calculated based on the weight of the total quantities of demolition waste generated. The base year total cost of disassembly phase was also applied once as capital cost and there was no last year of occurrence. The net present value of the (NPV) of disassembly of a unit archetype of the house scenario in question can be represented by equation 4.16 above.

$$N_{vd} = F_{v,d}(1+d)^{-n} \qquad \text{(Equation 4.16)}$$

$F_{vd,n}$ = present disassembly cost discounted to present value in year n (€).

The net present value of the operation phase of an archetype was calculated based on the annual operational energy costs (i.e. sum of yearly fuel costs). The net present value

(NPV) of the operational phase of an archetype of the house scenario in question can be represented by equation 4.17 below.

$$N_{vo} = \sum_{n=0}^{k} F_{vo,n} (1+d)^{-n} \qquad \text{(Equation 4.17)}$$

N_{vo} = is the net present value (NPV) of operation phase.

$F_{vo,n}$ = present value operation energy discounted to present value in year n to last year of occurrence, k.

LCC of the population of housing at archetype level

The sum of net present values (NPVs) across life cycle phases yielded the total life cycle costs of an archetype for the house scenario in question during its life span. In summary, the calculation of the LCC of a given house scenario involves identifying and summing all present costs by the year incurred and discounting these to their present values. The life cycle cost (LCC) of a given unit archetype of the house scenario in question can be represented by equation 4.18 below.

$$N_{tot} = F_{vm} + F_{vr} + F_{vd} + F_{vo} \qquad \text{(Equation 4.18)}$$

N_{tot} = Life cycle cost (total net present values) of a unit archetype of a given house option.

LCC at national stock level

The life cycle cost of the population of housing can be estimated using archetype LCCs. The life cycle cost of the exiting Irish housing stock across house scenarios was calculated as the sum of the product of the life cycle cost for the individual unit archetypes and the corresponding number of houses in the population for which the unit archetype is representative. This can be represented by equation 4.19 below.

$$N_{tot,stock} = \sum_{a=1}^{b} N_{tot} * N_a$$

(Equation 4.19)

$N_{tot,\ stock}$ = life cycle cost of the exiting Irish housing stock for a given house scenario

N_a = number of houses for which the unit archetype is representative in the housing stock.

4.4.3 Marginal abatement costs (MAC)

While MAC has been discussed in Chapter 2, the methodology used in calculating MAC is discussed in this section. The marginal abatement cost can be represented by equation 4.20 below (Hasanbeigi et al):

$$M = \frac{(\text{Full cost of abatement option}) - (\text{Full cost of basecase option})}{(CO_2 \text{ emissions from basecase option}) - (CO_2 \text{ emissions from abatement option})}$$

(Equation 4.20)

Where, M is the marginal abatement cost (€/tCO_2). The full costs of both the abatement and base-case options are expressed in euro (€) while the CO_2 life cycle emissions across scenarios are expressed in tonnes of CO_2 (tCO_2). In this study, the marginal abatement cost for house retrofit scenarios is calculated by modifying equation 4.20 to equation 4.21:

$$M = \frac{(\text{Cost of retrofitted scenario}) - (\text{Cost of BaseCase scenario})}{(\text{Emissions from BaseCase scenario}) - (\text{Emissions from retrofitted scenario})}$$

(Equation 4.21)

The procedure for the calculation of MAC involves the following steps. First, the life cycle costs of house retrofit scenario are obtained as calculated in the LCC section (See Figure 4.13). Next, CO_2 emissions due to both the no-intervention and the two retrofit options are obtained from the results of the hybrid analysis in Section 4.2 under LCA methodology. All of these combined in equation 4.20 to form the basis for the MAC calculations.

However, in calculating the MAC, the following assumptions were made – (1) No changes in the efficiency of the existing systems; (2) CO_2 emissions associated with grid electricity stay same in the future; and (3). It is also assumed that the house energy consumption remains unchanged over the 50 years service live of the building. For example, a change in any of the above is likely to result in deviations in both the amounts of emissions and life cycle costs associated with the current calculation of the MAC.

4.5 Conclusions to Chapter 4

The key conclusions from this chapter are:

- A new approach for characterising housing stock into representative archetypes has been developed.
- Similarly, hybrid-LCA model comprising the developed archetype model, an energy model and an LCA software model for the existing Irish housing has been developed and validated with statistics and previous studies.
- The study is based on the use of a combination of sources of data. The study uses process emission intensities for materials quantities for which only process data is available. Similarly, input-output (I-O) emissions intensities are applied for materials quantities for which only I-O data is available.
- The study is based on the use of 2005 baseline (i.e. year of survey of the housing database) input parameters of the housing database to evaluate the pre1960 – 2002 proportion of the existing Irish housing stock.

- The study focuses on retrofit measures that are within the contemporary obtainable practices, and in particular the examples of feasible retrofits identified from literature.
- This chapter has shown that the hybrid-LCA model developed in the thesis can be used to analyse a complete view of the emissions attributable to the existing Irish housing stock.
- The model can be adapted to other countries, using the respective country energy/emissions intensities.
- In the context of the study, the following assumptions were made:
    - Energy supply system will be constant during the entire lifetime of the building.
    - A 50-year service life is assumed for all dwellings.
    - Recyclers are located at approximately 50 km from the building.

Chapter 5: Results and Discussion

5.1 Overview

This chapter presents the results and discussion of: the characterisation of the existing Irish housing stock into archetypes; and the life cycle energy, emissions and costs for all archetypes under the 'BaseCase', 'Current Regulations' and 'Passive House' scenarios. Results are extended to the entire population of dwellings and marginal abatement costs (MAC) including fuel costs are estimated.

5.2 Archetype development

In this section, the results and discussion of the methodology used in the development of archetypes is discussed.

5.2.1 Statistical analysis results and discussion

In this section, the results of the statistical analysis that was performed in Chapter 4 in the development of archetypes is presented and discussed. The results of the linear regression indicate a coefficient of determination (R^2) of .467 (See Table 5.1), indicating that 46.7% of the variance in household Total Energy Use is described by the model. Five of the variables are significant at the 5% levels; indicating a confidence that these variables influence the dependent variable, Total Energy Use. Variables which are significant at this level include: Typical Weekly Occupancy Pattern (heating season) (high), Internal Temperature (^{o}C), Air Change Rate (ac/h), Number of storeys and Household composition (3 adults, 2 children). Table 5.1 gives the results of MLRA model; column headings are explained below.

- Un-standardised Regression Coefficient (B) – gives the change in the dependent variable (Total Energy Use) due to a change of one unit of a predictor variable. The relationship between Air Change Rate (ac/h) and Total Energy Use indicates the greatest strength with an un-standardised coefficient of 145.72 (i.e. significantly different from 0; for every unit increase in house air change rate there is an increase of 145.72kWh/m^2.yr in house energy use) showing that Air Change Rate (ac/h) contributes significantly to the estimation of Total Energy Use. This is followed by un-standardised coefficients for Internal Temperature (^{o}C) of 76.37kWh/m^2.yr, Typical Heating Season Weekly Occupancy Pattern (high) of 60.85kWh/m^2.yr, Number of storeys of 46.31kWh/m^2.yr, and Household composition (3 adults, 3 children) 73.38kWh/m^2.yr. The high un-standardised coefficient for air change rate can be explained as most of the sample houses indicate significant air tightness. It would be recalled that in Section 3.2.1 under 'Generic Characteristics' that an argument of the presence of excessive air leakage, defined as an air change rate greater than 0.5 air changes per hour under normal air pressure found in only 37% of dwellings was supported. Moreover, Sinnott and Dyer (2011), report on the air permeability of the existing Irish housing, and found the pre-1975, 1980's and 2008 dwellings to be 7.5m^3/hr/m^2, 9.45m^3/hr/m^2 and 10.45m^3/hr/m^2, respectively, and that new dwellings cannot be automatically be assumed more air-tight than older buildings. Similarly, the high un-standardised coefficient for internal temperature can be attributed to the presence of sample houses with high heating energy. For example, one such example is a 47m^2 floor area house running on a peat-fired back-boiler with main heat source seasonal (SEDBUK) efficiency of 50% and 709.4kWh/m^2.yr heating energy.

- Standardised Coefficient (Beta) – indicates which independent variables have the greatest effect on the dependent variable, since the variables have different measurement units subject to certain data quality assumptions. Internal Temperature (^{o}C) is the most significant in predicting Total Energy Use with a standardised coefficient of 0.241, followed by Typical Heating Season Weekly Occupancy Pattern (heating season) (high) of 0.233, Household composition (3 adults, 3 children) of 0.216, Number of storeys of 0.212 and Air Change Rate (ac/h) of 0.208.
- Significance level of a predictor variable quantifies the probability that the relationship identified between Total Energy Use and the independent variables is chance. A significance threshold of 5% was chosen.

Table 5.1: Multiple linear regression results

Reference	**Explanatory variables**	**Un-standardized Coefficients**		**Standardized Coefficients**	**t-stat**	**p-value**
		B	**Standard error**	**Beta**		
	Constant	-1133.8	771.95		-1.469	.145
1	Wall overall U-value (W/m^{2}K)	5.15	23.05	.023	.224	.824
2	Roof overall U-value (W/m^{2}K)	-19.94	22.06	-.080	-.904	.368
3	Floor overall U-value (W/m^{2}K)	18.0	13.63	.112	1.321	.189
4	Window overall U-value (W/m^{2}K)	38.42	42.32	.094	.908	.366
5	Air change rate (ac/h)	145.72	61.16	.208	2.383	.019*
6	Internal temperature (^{o}C)	76.37	37.45	.241	2.039	.044*
7	Semi-detached	-11.71	27.36	-.041	-.428	.670
8	Mid-terrace	17.90	33.15	.056	.540	.590
9	End-terrace	-12.35	52.90	-.019	-.233	.816
10	Purpose-built apartment	-7.70	55.91	-.012	-.138	.891
11	Converted apartment	-65.56	79.32	-.064	-.826	.410
12	Heating system (%)	-2.25	1.18	-.217	-1.904	.060

Reference	Explanatory variables	Un-standardized Coefficients		Standardized Coefficients	t-stat	p-value
		B	**Standard error**	**Beta**		
13	House volume (m^3)	-.012	.057	-.023	-.213	.832
14	Number of storeys	-46.30	22.14	-.212	-2.092	.039*
15	Household composition (2adults, 2 children)	7.31	29.62	.030	.247	.806
16	Household composition (3 adults, 3 children)	73.38	35.60	.216	2.061	.042*
17	Household composition (4 adult, 4 children)	-26.70	40.96	-.068	-.652	.516
18	Household composition (5 adult, 5 children)	5.60	64.51	.008	.087	.931
19	Cylinder insulation thickness (mm)	-1.14	.673	-.145	-1.689	.094
20	DHW cylinder size (litre)	.324	.204	.151	1.584	.116
21	Pipe-work (mm) (insulated)	-21.22	21.36	-.085	-.994	.323
22	Typical weekly occupancy pattern (Heating Season) (medium)	10.22	25.98	.042	.393	.695
23	Typical weekly occupancy pattern (Heating Season) (high)	60.85	28.15	.233	2.162	.033*
24	Immersion heater weekly frequency	1.06	.621	.142	1.708	.090
25	Electricity tariffs (day/night)	27.25	27.10	.077	1.006	.317
26	Draught (persistent)	54.07	38.46	.115	1.406	.163
27	Draught (some)	.707	19.57	.003	.036	.971
28	Humidity (Occassional damp)	-12.38	21.21	-.046	-.584	.561
29	Humidity (typically damp)	-132.58	68.93	-.158	-1.923	.057
30	Thermostatic radiator valve control (trvc)	6.96	35.70	.019	.195	.846
31	Fulltime temperature control (fttzc)	.317	42.57	.001	.007	.994
Note: $R^2 = .457$; *($p < 0.5$)						

*Significant at the 5% level.

**List of dummy variables: detached house, Typical Heating Season Weekly Occupancy Pattern (heating season) (low), Pipework (Insulated), Temperature control (Basic), Household composition (2 adults, 2 children), Electricity tariffs (Standard), Draught (No draught) and Humidity (Occasionally damp).

As the MLRA has failed to fully explain the variables that are required for the energy analysis, despite the application of all techniques that will ordinarily lead full explanation of the predictors by the model, this study assumed that there is a problem with the data. One of the causes of predictive models to fail to explain the predictors is sampling issue (Granville, 2011). However, since this is the only data available for the thesis, it became necessary to supplement the selected data above from literature based on previous energy efficiency improvement studies.

In the previous section the four key variables impacting house energy use were determined based on a multiple linear regression analysis of the EPSIH database. In this section, these variables are adjusted and combined with other information to determine the final list of variables required in the formation of archetypes. The final list of household key variables obtained from MLRA was streamlined to remove behavioural variables and those with very small effects. It was then supplemented with variables which are undisputedly important based on literature/or theory as outlined below:

Although five variables were found to be significant at the 5% threshold in the MLRA (see above), Internal Temperature (^{o}C), Typical Weekly Occupancy Pattern (Heating Season) (low/medium/high), Typical Heating Season Weekly Occupancy Pattern (heating season) (high) and Household composition (3 adults, 3 children) were excluded since the final archetypes will operate under average, long-term temperatures and occupancy. These variables are ones that are determined by the behaviour of occupants, and for the stock modelling objectives of this study occupant-related variables are standardised. Number of storeys is also excluded since it is not commonly used in housing energy analysis. Thus, only one key variable was selected from the results of the regression analysis, namely Air Change Rate (ac/h).

As one key variable selected from the results of the regression analysis is not sufficient to provide the necessary parameter inputs to adequately define representative archetypes and perform energy analysis, it was therefore, important to obtain supplementary variables. Eight supplementary variables were obtained from the ranking of key variables in Table 2.6 and are justified as follows:

i. Wall, Roof, Floor and Window U-values were selected based on their importance in determining energy consumption, as reported in the literature (see Table 2.6).

ii. Similarly, Dwelling Type was chosen based on Table 2.6, and in particular as it is a major determinant of energy for space heating whilst also determining the number of exposed walls and the average floor area (both of which influence the dwelling heat loss) (Firth, 2009). For example, it is possible to have a terrace and detached house with the same values for all the parameters, such as U-values, air change rate, and so on, but they would have very different energy consumptions because of the difference in the number/area of external walls.

iii. Heating System Efficiency (%) was selected based on the ranking of variables in Table 4.1, and in particular as the primary energy use for operating a building depends mainly on the processes in the energy supply systems for electricity and heat (Gustavsson and Joelsson, 2010). It should be noted that primary energy refers to the total energy required to provide the end user with delivered energy, including energy losses due to transformation and delivery.

iv. DHW Cylinder Insulation Thickness (mm) was selected because heat losses can be significant due to inadequate insulation.

v. Floor Area (m^2) has been selected based on literature, and in particular as it is more commonly used for housing energy analysis than number of storeys.

With the selection of eight supplementary variables above, the final list in the development of archetypes in Step 4 below represents nine. These include the one key variable obtained from the MLRA and the eight supplementary variables obtained above - Wall U value (W/m^2K), Roof U value (W/m^2K), Floor U value (W/m^2K), Window U-values, Air Change Rate (ac/h), Heating System Efficiency (%), Dwelling Type, Floor Area (m^2), DHW Cylinder Insulation Thickness (mm). This number was considered sufficient as the variables were considered most important based on Table 4.1, and in particular as they have been individually justified above.

Figures 5.1 and 5.2 are histograms of wall and roof U-values from the EPSIH database. Figure 5.1 shows a bimodal mixture of 2 normal distributions with wall U-values clustering around two peak values from which representative values were chosen. The first mode is between 0.375 and 0.5 W/m^2K. The second mode is between 1.5 and 1.625 W/m^2K. Figure 5.2 represents a skewed distribution, and the mode is at or near the left tail of the data and so it appears not to be a good representative of the centre of the distribution. Having considered the three metrics of mean, median and mode in regard to summarising and characterising the dataset, the mean was considered to serve well as the representative value ("typical value"), and is between 0.33 and 0.46 W/m^2K. The chosen representative values for these two variables are:

a. Wall U-value: between 0.375 and 0.5 W/m^2K; and between 1.5 and 1.625 W/m^2K.

b. Roof U-value: between 0.33 and 0.46 W/m^2K.

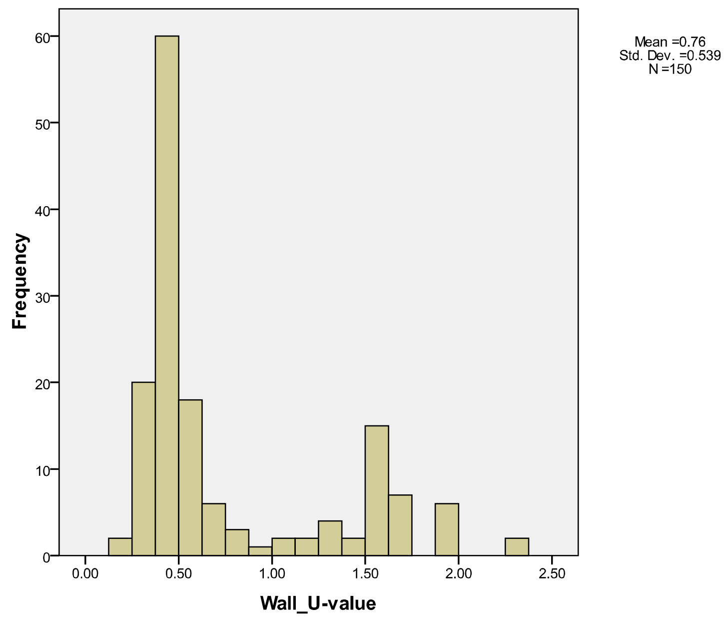

Figure 5.1- Frequency histogram of wall construction type

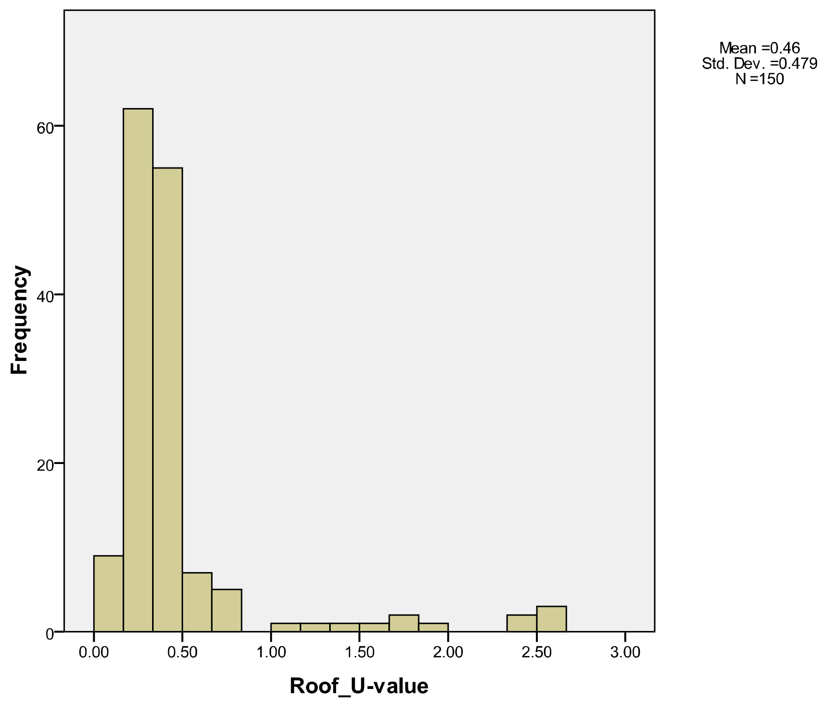

Figure 5.2 - Frequency histogram of roof construction type

On the basis of the above chosen representative U-values for Wall and Roof U-values, together with knowledge of construction details/building regulations, representative construction details were chosen as follows:

a. 0.375 W/m^{2}K and 0.5 W/m^{2}K: full fill cavity wall with 100mm mineral wool insulation and partial fill cavity wall with 75mm mineral wool insulation; and 1.5 and 1.625 W/m2K: un-insulated cavity wall.

b. 0.33 W/m^{2}K and 0.46 W/m^{2}K: roof with 120mm mineral wool insulation between the joists or 150mm mineral wool insulation between the rafters and 75mm mineral wool insulation between the joists or 100mm mineral wool insulation between the rafters.

As shown (i.e. as circled) in Figure 5.3, there are three clusters of data points from which archetype parameters representative of a combination of building construction details were chosen for combined roof and wall construction details. Cluster "A" represents the following values (Roof U value, Wall U value): (0.17, 0.25), (0.33, 0.25), (0.17, 0.375), (0.33, 0.375), (0.33, 0.5) and (0.46, 0.5) W/m^{2}K; Cluster "B" represents (0.33, 1.5), (0.33, 1.625), (0.46, 1.625) and (0.46, 1.75) W/m^{2}K; and Cluster "C" is represented by (0.33, 2.0) W/m^{2}K.

The final parameters of roof and wall construction details in the development of archetypes are as follows:

1. Cluster "A"

- All values of cluster "A" above were aggregated to (Roof U value, Wall U value): (0.33, 0.375), (0.33, 0.5), (0.46, 0.5) W/m^{2}K.

2. Cluster "B"

- All values of cluster "B" were aggregated to: (0.46, 1.625) W/m^{2}K.

Thus, the archetype parameters were chosen for: Dwelling Type Class; Wall Construction Type; Roof Construction Type; Floor Construction Type; Window Type; Air Change Rate; Heating System Efficiency; DHW Cylinder Insulation; and Floor Area. With the above procedures a total of 13 representative archetype houses have been developed using 9 classes of construction detail (construction type) and statistical categories of 9 key variables of energy use. (Frequency histograms and cluster analysis of the remaining variables are presented in Appendix 2).

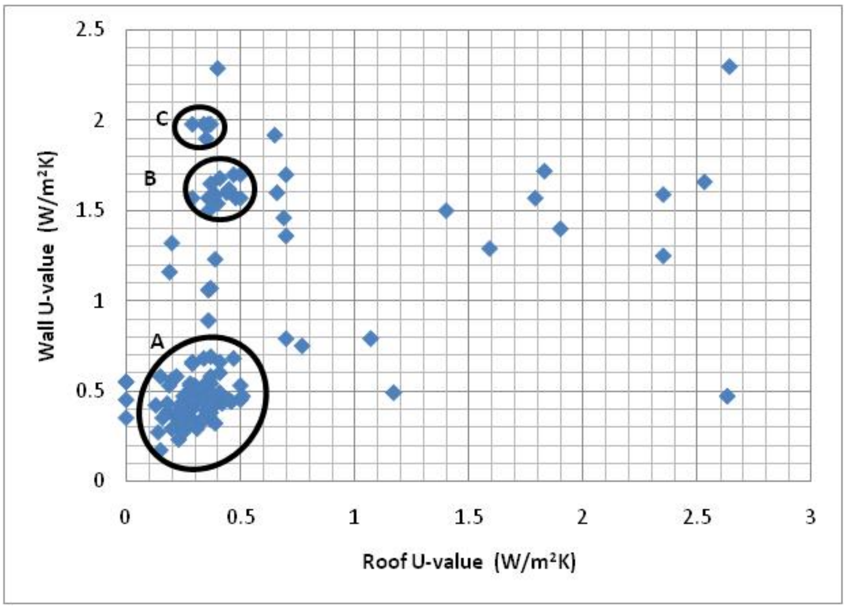

Figure 5.3 - Scatter plot: Roof vs. Wall construction types

Description of the archetypes

Table 5.2a illustrates the final archetypes identified in this study. Similarly, Table 5.2b gives the summary of the retrofit measures to all archetypes for all retrofit scenarios and is linked to the summarised description of the archetypes. For each of the thirteen archetypes the parameters for all nine key variables are shown together with a description of the characteristic construction details corresponding to these parameters.

The thirteen archetypes were representative of 98 dwellings in the sample of 150 (or 65% of the sample). The remainder of figures and tables on archetype development are in Appendix 2.

Table 5.2a: Formation of archetypes

Building Element Variable										
Dwelling Type	**Archetype number**	**Wall U-value ($W/m^2.K$)**	**Roof U-value (W/m^2K)**	**Window U-value ($W/m^2.K$)**	**Floor U-value ($W/m^2.K$)**	**Floor Area (m^2)**	**Heating Systems %**	**Air Change Rate (ac/h)**	**DHW Cylinder Insulation (mm)**	**Sample Distribution**
Detached (House/Bungalow)	1	Partial fill cavity wall, ceiling insulation, double-glazed UPVC window, insulated concrete solid floor, conventional gas/oil boiler, DHW cylinder lagging jacket								
		0.5	0.33	3.0	0.5	133	80	0.87	30	23
	2	Partial fill cavity wall, ceiling insulation, double-glazed UPVC window, insulated solid floor, conventional oil/gas boiler, DHW cylinder lagging jacket								
		0.5	0.46	3.0	0.58	133	80	0.74	30	11
	3	Partial fill cavity wall, ceiling insulation, draught-proofed single-glazed wooden window, insulated solid floor, conventional oil boiler, DHW cylinder lagging jacket								
		0.5	0.46	4.75	0.58	133	70	0.67	30	6
	4	Insulated single-leaf wall, rafter insulation, double glazed UPVC window, insulated solid floor, conventional oil/gas boiler, DHW cylinder foam								
		0.5	0.33	3	0.58	133	80	0.87	37	8
	5	Partial fill cavity wall, rafter insulation, double-glazed UPVC window, insulated solid floor, conventional oil/gas boiler, DHW cylinder foam								
		0.5	0.33	3.0	0.58	133	80	0.74	35	6
	6	Full fill cavity wall, ceiling insulation, low-e UPVC window, insulated solid concrete floor, conventional oil/gas boiler, DHW cylinder foam								
		0.375	0.33	2.25	0.5	133	80	0.67	37	4
Semi-Detach	**7**	Insulated single-leaf wall, ceiling insulation, double- glazed wooden window, insulated solid floor, conventional oil/gas boiler, DHW cylinder foam								

Dwelling Type	Archetype number	Wall U-value ($W/m^2.K$)	Roof U-value (W/m^2K)	Window U-value ($W/m^2.K$)	Floor U-value ($W/m^2.K$)	Floor Area (m^2)	Heating Systems %	Air Change Rate (ac/h)	DHW Cylinder Insulation (mm)	Sample Distribution
Building Element Variable										
		0.5	0.33	3.25	0.5	100	80	0.94	35	6
	8	Partial fill cavity wall, ceiling insulation, double-glazed UPVC window, insulated solid floor, conventional oil/gas boiler, DHW cylinder lagging jacket								
		0.5	0.33	3.0	0.5	100	80	0.94	50	3
	9	Insulated single-leaf wall, rafter insulation, double-glazed UPVC window, insulated solid floor, conventional oil/gas boiler, DHW cylinder lagging jacket								
		0.5	0.33	3.0	0.5	100	80	0.87	30	3
	10	Partial fill cavity wall, ceiling insulation, double-glazed UPVC window, insulated solid floor, conventional oil/gas boiler, DHW cylinder foam								
		0.5	0.33	3.0	0.5	100	80	0.94	35	12
Mid-terraced/Apartment (i.e. comprising ground, first and second floors)	11	Partial fill cavity wall, ceiling insulation, double-glazed wooden window, insulated solid floor, conventional oil/gas boiler, DHW cylinder lagging jacket								
		0.5	0.33	3.25	0.5	100	80	0.87	30	8
	12	Partial fill cavity wall, rafter insulation, double-glazed wooden window, insulated solid floor, conventional oil/gas boiler, DHW cylinder lagging jacket								
		0.5	0.33	3.25	0.5	100	80	0.87	30	5
	13	Un-insulated cavity wall, rafter insulation, draught-proofed single-glazed wooden window, un-insulated suspended timber ground floor, conventional oil/gas boiler, DHW cylinder foam								
		1.625	0.46	4.75	0.58	133	80	0.94	35	3
Total sample distribution = 98										
Total sample houses =150										
Percentage covered = 65										

Table 5.2b: Summary of archetypes and the refurbishment required to achieve both Current Regulations and Passive House scenarios.

	Archetype Description		Scenario		
Archetype reference*	**Variable**	**Material**	**BaseCase**	**Current Regulations**	**Passive House**
1-5, 7-12	Partial fill cavity wall	Mineral wool (slab)	$0.5W/m^2K$	$0.21W/m^2K$	$0.12W/m^2K$
6	Full fill cavity wall		$0.375W/m^2K$		
13	Un-insulated cavity wall		$1.625\ W/m^2K$		
4, 7, 9	Single-leaf wall		$0.5\ W/m^2K$		
1, 6-8, 10-11	Ceiling insulation	Mineral wool (quilt)	$0.33W/m^2K$	$0.16W/m^2K$	$0.1W/m^2K$
2-3			$0.46W/m^2K$		
4-5, 9, 12-13	Rafter insulation		$0.33W/m^2K$		
2-3, 13			$0.46W/m^2K$		
1, 6-12	Insulated solid floor	Rigid foam (mm)	$0.5W/m^2K$	$0.21W/m^2K$	
2-5, 13	Un-insulated suspended timber ground floor		$0.58W/m^2K$		
7-8, 10, 13	Air change rate	Sealant	0.94ac/h	0.35	0.25
1, 4, 9, 11-12			0.87 ac/h		
2, 5			0.74 ac/h		
6			0.67 ac/h		
1-2, 4-5, 8-10	Windows	UPVC and glass	Double-glazed UPVC	Triple-glazing (1 low-emissivity coating, 2 gaps with air to achieve a U-value of 1.6.)	Triple-glazing (1 low-emissivity coating, 2 gaps with argon gas, and integral draught proofing to achieve a U-value of 0.8 W/m2K (Gustavsson, 2010)
6			Low-e UPVC		
3,13			Single-glazed timber		
7, 11-12			Double-glazed timber		
1-3, 9, 11-12	DHW cylinder	Factory-applied coating of polyurethane foam	30**	50mm	75mm
5, 7, 10, 13			35***		
4, 6			37***		
8			50**		
1-2, 4-6	Heating system/Low emissions technologies	Not available	Conventional oil boiler (80% efficiency)	Condensing/boiler, Solar hot water - $4m^2$ solar flat plate system	Ground source heat pump, Solar hot water - $4m^2$ solar flat plate system, Mechanical ventilation plus heat recovery (MVHR) and PV system
3			Conventional oil boiler (70% efficiency)		
7-13			Conventional gas boiler (80% efficiency)		Air source heat pump, Solar hot water - $4m^2$ solar flat plate system, Mechanical ventilation plus heat recovery (MVHR) and PV system

Discussion on archetype development

It has been mentioned previously that, 53.3% of the variation in house energy use is not explained by the model. This is not surprising because occupancy behaviour, for which data were not available, will have a significant impact on the main energy use. Occupancy is ignored in the analysis because long-term average occupancy is best applied for stock modelling purposes and the houses are occupied by many different types of users (young couples, families with young children, families with teenagers, older couples, pensioners etc.) over their lifespans. Furthermore, some data exhibited evidence of weak interactions among two or more variables, possibly due to the upgrade of individual building elements over the years so that, for example, wall, window and roof U-values were not clustered. In some situations, it may be impossible to establish if an outlying point is bad data as outliers may be a result of random variation or indicate something scientifically interesting (NIST 2011). For example, when buildings are renovated, it is expected that wall and roof U-values will comply with the current building regulations. So it is would be expected to see some clustering between those variables. Furthermore, while (Clinch and Healy, 1999) found that the levels of cavity-wall insulation in Ireland were at 42% in 1998 and remained static over the period 1996–2001, the levels of roof insulation were significantly better, with almost four-fifths of the stock possessing this energy efficiency measure, mainly a result of the State-funded attic-insulation scheme of the 1980s (Healy and Clinch, 2004). It should also be noted that the present study found that roof U-values were in closer compliance with current building regulations than wall U-values.

5.3 Life cycle assessment results and discussions

The results of the LCA are presented for each archetype by life cycle phase and entire population of housing at average dwelling and national housing stock levels. In this study, the 'average dwelling' is the 'weighted mean archetype' by number of representative archetypes in the population.

5.3.1 Operational phase

Tables 5.3 – 5.8 indicate the results of the operational phase at archetype, 'weighted mean archetype' and archetype national stock levels for the different scenarios. Results show that although operational phase consumption and emissions are much greater than any other phase, there are a wide range of results for this phase for house scenarios.

Operational phase impacts at archetype level

Table 5.3 indicates the results of operational primary energy use by archetype for each scenario. Overall, operational primary energy use at archetype level for the BaseCase scenario ranges from: 384– 614kWh/m^2.yr or 99.6% – 99.8% for detached house archetypes, 271kWh/m^2.yr or 99.5% for semi-detached house/end-terraced house archetypes, and 258 – 500kWh/m^2.yr or 99.6% - 99.7% for mid-terraced house/apartment archetypes. The higher range of primary energy use in detached house archetypes reflects their higher floor and window areas and the use of oil-fired boilers when compared to the other two archetypes. It should be noted that the high deviation exhibited by Archetype 3 within the detached archetype house group is due to its low level of envelope insulation when compared to other archetypes within the group. For example, it exhibits single-glazed wooden windows, lowest oil-fired heating system efficiency and roof insulation level. Semi-detached house archetypes have no variation due of their similar u-values and areas. The higher variance noticed in mid-terraced house/apartment archetypes compared to the two dwelling types is due mainly to the presence of Archetype 13, which has the same floor area as those of detached house archetypes, especially at it has the poorest overall levels of envelope insulation compared to the remaining 12 archetypes. For example, it exhibits an un-insulated cavity wall, singled-glazed wooden windows, un-insulated suspended timber ground floor and a low level of roof insulation.

Table 5.3: Primary energy use (kWh/m^2.yr) of all archetypes across life cycle phases

Dwelling type		BaseCase					Current Regulations					Passive House standard				
	Archetype Reference	Retrofit	Maintenance	Operation	Disassembly	Total	Retrofit	Maintenance	Operation	Disassembly	Total	Retrofit	Maintenance	Operation	Disassembly	Total
Detached house archetype	1	0	1.10	428	0.61	429	10.2	2.95	211	0.85	225	12.81	3.59	120	0.80	137
	2	0	0.65	509	0.68	510	10.3	1.29	248	1.18	261	12.9	1.30	111	1.11	126
	3	0	0.66	613	0.82	614	10.2	1.69	220	1.18	233	12.6	1.16	111	1.10	126
	4	0	0.91	449	0.60	450	9.8	2.75	211	0.83	225	12.3	3.44	111	0.80	128
	5	0	1.31	448	0.62	450	12.0	3.08	211	0.88	227	14.5	3.75	110	0.80	129
	6	0	1.11	384	0.61	386	10.9	3.08	211	0.86	226	13.6	3.68	110	0.80	128
Semi-detached/end-terraced house archetype	7	0	0.79	271	0.45	272	5.5	2.62	151	0.51	160	7.9	3.31	79	0.49	91
	8	0	0.78	271	0.45	272	5.4	2.61	151	0.51	160	8.2	3.30	79	0.49	91
	9	0	0.82	271	0.45	272	5.5	2.66	151	0.51	160	7.9	3.33	79	0.49	91
	10	0	0.80	271	0.45	272	5.5	2.63	151	0.51	160	7.9	3.32	79	0.49	91
mid-terraced house/apartment archetype	11	0	0.72	271	0.44	272	5.5	2.56	151	0.51	160	7.9	3.26	79	0.49	91
	12	0	0.66	258	0.44	259	4.8	1.99	144	0.50	151	6.6	2.50	81	0.48	90
	13	0	0.46	500	0.81	501	8.5	0.92	191	0.94	201	10.3	0.98	107	1.09	120

When viewed in terms of the ratio to life cycle energy, the following general trends can be inferred from the results of the BaseCase scenario:

- Detached house archetypes show a higher range of operational primary energy use (approx. 99.6 - 99.8% of the life cycle's total) when compared to semi-detached house/end-terraced house archetypes and mid-terraced house/apartment archetypes. These results are not surprising since the construction phase of the buildings were not evaluated. The embodied energy/emissions attributable to the BaseCase dwelling are those associated with its ordinary maintenance only. Moreover, previous studies show that the operation energy use of buildings constructed to conventional standards represents in excess of 90% of the life cycle energy (Fossdal 1995, Feist, 1997).

- Semi-detached house/end-terraced house archetypes indicate similar ratios of operational primary energy use (99.5% of the life cycle's total) due to those reasons earlier discussed above.
- Although Mid-terraced house/apartment archetypes have floor and window areas relatively similar to those of semi-detached house/end-terraced house archetypes, their ratio of operational to life cycle primary energy use (99.6% – 99.7% shows higher deviations, due to the presence of archetype 13 based on same reasons earlier discussed above.

Scheuer et al, (2003) assessed the life cycle phases of a six-storey building in Michigan, US and found operational energy for heating, ventilation and electricity to account for 94.4% of the life cycle primary energy consumption. This supports the results of the semi-detached house/end-terraced house archetypes indicated above. The difference is mainly due to higher proportion of embodied energy as Scheuer et al. account for the complete pre-use phase of the building (i.e. 2.2% of the primary energy) compared to this study which accounts only for the ordinary maintenance of the BaseCase scenario.

It is difficult to directly verify these findings in literature because most studies found are based on energy end-use and in those few presented in primary energy requirements usually do not include fuel supply chain impacts occurring outside the country of study. Any attempt to convert the results of such studies to primary energy use is impossible since the heat and electricity fuel mix data are difficult to obtain for these studies. However, an indirect verification was undertaken of the results. The weighted mean operational primary energy use at archetype level was calculated as the sum of the product of the archetype operational primary energy and the corresponding number of sample houses for which the archetype is representative in the total number of stock archetypes divided by the total number of archetypes. This was found to be 404kWh/m^2.yr.

Table 5.4 shows the results of weighted mean annual operational energy use compared to other results from literature. The weighted mean annual operational primary energy calculated in this study was found to be 45,478kWh in 2005. The national statistics figure for the average dwelling annual operational energy of 25,850kWh (split into 23,350kWh of heat and 5,000kWh of electricity) in Ireland for same year (DCENR, 2009) was converted to mean weighted operational primary energy by multiplying these figures by the corresponding primary energy conversion factors (heat, 1.0 and electricity, 2.86) (SEAI, 2006) and dividing the sum for heat and electricity by the average floor area (104m^2) for same year (HSEU, 2006). The weighted mean annual operational primary energy use was then estimated to be 30,150kWh or 338kWh/m^2 for same year. A previous Irish study, Clinch et al (2001a) also assessed the Irish housing stock to predict end-use energy and CO_2 savings and calculated average dwelling operational primary energy use to be 333kWh/m^2.yr. Table 5.4 illustrates this comparative analysis

The mean weighted operational primary energy average requirement per m^2 was therefore found to be generally consistent with both national statistics and literature. Any differences can be explained as national statistics and literature values did not include energy for fuel supply chain processes that occurred abroad. This study estimated this to be around 16%, 8% and 12% of operation energy representing oil, gas and electricity, respectively, which were included in the calculations. The GaBi software tool used in this study accounts for upstream and lateral activities of fuel supply chain processes activities from abroad to home delivery. It should be noted that primary energy supply chain processes refer to upstream and lateral activities for energy production and distribution (e.g. power station operation and maintenance, transmission network maintenance and operation diesel road transport, etc).

Table 5.4: Comparison of average operational energy use with literature

	Study	Operational end-use energy	Average operational primary energy use (converted)		Comment
		per dwelling (kWh/.yr)	per dwelling (kWh/.yr)	per m^2 floor area ($kWh/m^2.yr$)	
1	National statistics (DCENR, 2009)	25,850	35,150	338	Does not include international sources of impacts for fuel supply chain processes
2	Clinch et al (2001a)	24,128	32,331	333	Does not include international sources of impacts for fuel supply chain processes
3	Present study	-	45,478*	404*	Include both non-domestic and domestic sources of impacts for fuel supply chain processes

*Study figure (mean weighted operational primary energy)

Another factor for the difference is that national statistics results were derived based on top-down models. Unlike process-based hybrid analysis, a top-down technique is a statistical input-output approach, which relies on division of the whole economy into different sectors and uses economic inputs and outputs between the sectors to calculate the energy and associated environmental impacts. Specific sectors may not be available in I-O table, raising concerns about data availability. Surely, an incomplete system boundary will result in loss of accuracy. Inaccuracies are also likely to occur in top-down models due to dissimilarities between the real energy requirement of a given process and the sector average.

Overall, in comparison with other studies with similar climatic conditions, the high operational energy result can be attributed to the particularly energy-inefficient housing stock especially as residential energy-efficiency programme is likely to have a greater impact on relative energy consumption in Ireland than most other countries (Clinch et al. 2001b).

Operational phase improvement potential at archetype level

Table 5.3 also indicates the relative environmental improvement for all retrofit scenarios compared to the BaseCase scenario. As can be seen all retrofit scenarios yield significant operational improvement compared to the BaseCase scenario. Overall, and for most archetypes the operational primary energy reduced by at least 44% and 69% for the Current Regulations and Passive House standard scenarios, respectively compared to the BaseCase scenario.

For the Current Regulations scenario, detached house archetypes show a higher range of operational primary energy use (211 – 248kWh/m^2.yr) than the other two archetypes. Semi-detached house/end-terraced house archetypes indicate the lowest operational primary energy use, representing 151kWh/m^2.yr. Mid-terraced house/apartment archetypes represent a range of 144 - 159 kWh/m^2.yr.

The above reductions in operational energy resulted from the incorporation of good thermal insulation of the envelope, substitution of the existing oil-fired boiler with gas-fired boiler, reduced thermal bridges, improved air tightness and low-energy glazing.

In a study by Feist, (1997), the author analysed and compared the life cycle primary energy of six construction standards in Germany (i.e. six conventional buildings), and found that the primary energy use (after conversion) during the operation phase of a low-energy dwelling is 200kWh/m^2.yr. A low-energy building is defined as that having an operational primary energy of 202kWh/m^2.yr or lower Feist, (1997). This is further supported by another study, Sartori and Hestnes, (2006) that for low energy buildings, life cycle primary energy requirement falls within the range of 50-210kWh/m^2.yr. However, this will depend on the system boundary considered in the analysis. On the basis of same method undertaken above in the calculation of weighted mean operational primary energy for the BaseCase scenario, the weighted mean operational energy for the Current Regulations was found to be 192kWh/m^2.yr. The above findings of Feist (1997) therefore support the results of the operational energy use for the Current Regulations scenario presented in Table 5.3, and in particular when energy use for fuel supply chain processes outside the country of study is considered.

For the passive house standard scenario, detached house archetypes show a higher range of operational primary energy use (110% – 120kWh/m^2.yr). Semi-detached house/end-terraced house archetypes indicate the lowest operational primary energy use, representing 79kWh/m^2.yr. Mid-terraced house/apartment archetypes represent a range of 79% - 107 kWh/m^2.yr. This is higher than for Mid-terraced house/apartment archetypes due to the presence of Archetype 13 which has a floor area similar to those of detached house archetypes.

In general, when compared to the BaseCase scenario in terms of share (%) of operational emissions reductions, for the Passive House standard scenario, detached house archetypes indicate a higher range of overall operational primary energy reductions (71% - 82%) when compared to semi-detached house/end-terraced house archetypes (71%) and mid-terraced house/apartment archetypes (69% - 78%).

A further comparison to the BaseCase scenario indicates that the improvement in operational energy as evident above resulted from greater use of resources than in the case of Current Regulations. These include very good thermal insulation of the envelope, avoidance of delivered heat energy, prevention of thermal bridges, high air tightness, super-glazing (U-values $\leq$ 0.8W/m^{2}K) and mechanical ventilation with heat recovery.

Similarly, the work of Feist (1997) found that the annual operational primary energy use of Passive House buildings is around 80kWh/m^2.yr. In this study, using a similar verification method as the above, the weighted mean operational primary energy of the Passive House standard scenario was found to 101kWh/m^2.yr. The difference can be explained as the work of Feist (1997) does not account for the energy use and environmental impacts associated with fuel supply chain processes that occurred outside the country of study. Furthermore, Winther and Hestnes (1999) evaluated the life cycle energy use of a Norwegian passive house option to be approximately 150kWh/m^2.yr. However, their model included the pre-use phase, which may have been responsible for the higher figure. The above finding of Feist (1997) therefore supports the results of the operational energy use for the Passive House standard scenario presented in Table 5.3, especially when energy use for fuel supply chain processes outside the country of study is considered.

Similarly, Table 5.5 indicates global warming potential (kgCO_2-eq) for all archetypes across life cycle phases for the different house scenarios. The direct correlation between resource consumption and GHG emissions is emphasized as this table directly reflects that of the primary energy. These results represent the outputs from GaBi 4.4 LCA software for primary energy-related emissions of all archetypes for all house scenarios.

Like in the case of operational energy, the results show that although operational phase emissions are much greater than any other phase, there are a wide range of results for house scenario. Overall, operation emissions at archetype level for the BaseCase scenario range from: 97.3 – 154.9kgCO_2-eq/m^2/yr for detached houses, 65.5kgCO_2-eq/m^2/yr for semi-detached house/end-terraced house archetypes, and 62.4 – 120.1kgCO_2-eq/m^2/yr for mid-terraced house/apartment archetypes. The higher emissions by detached houses compared to the other two dwelling types can be explained by those reasons earlier given in the case of the results of primary energy.

Table 5.5: Global warming potential (kgCO_2-eq./m^2.yr) for all archetypes across life cycle phases

Dwelling type		BaseCase					Current Regulations					Passive House standard				
	Archetype Reference	Retrofit	Maintenance	Operation	Disassembly	Total	Retrofit	Maintenance	Operation	Disassembly	Total	Retrofit	Maintenance	Operation	Disassembly	Total
Detached house archetype	1	0	4.27	108.2	0.18	112.7	4.42	6.02	52.0	0.21	62.6	10.47	5.64	28.2	0.22	44.6
	2	0	2.17	128.7	0.20	131.0	4.46	2.85	60.1	0.22	67.6	10.52	2.74	28.4	0.22	41.9
	3	0	2.15	154.9	0.21	157.2	4.48	2.83	54.0	0.22	61.5	10.52	1.96	28.4	0.22	41.1
	4	0	4.24	113.6	0.19	118.0	4.28	5.99	52.0	0.22	62.5	10.32	3.31	28.6	0.22	42.4
	5	0	4.30	113.4	0.17	117.8	4.90	6.02	52.0	0.21	63.1	10.93	3.34	28.2	0.21	42.7
	6	0	4.27	97.3	0.18	101.7	4.64	6.03	52.0	0.51	63.2	10.72	3.34	28.2	0.21	42.5
Semi-detached/end-terraced house archetype	7	0	4.20	65.5	0.14	69.9	4.37	5.98	52.0	0.19	62.5	10.43	3.30	28.2	0.19	42.2
	8	0	4.20	65.5	0.14	69.9	3.17	5.95	37.3	0.13	46.6	9.26	3.26	20.3	0.13	33.0
	9	0	4.21	65.5	0.14	69.9	3.19	5.95	37.3	0.13	46.6	9.19	5.58	20.3	0.13	35.2
	10	0	4.20	65.5	0.14	69.9	3.19	5.95	37.3	0.13	46.6	9.15	3.26	20.3	0.13	32.9
mid-terraced house/apartment	11	0	4.17	59.9	0.15	64.2	3.10	5.92	35.5	0.13	44.7	16.59	3.24	20.7	0.13	40.7
	12	0	4.17	62.4	0.15	66.7	3.10	5.92	35.5	0.13	44.7	16.57	3.24	20.7	0.13	40.7
	13	0	2.13	120.1	0.21	122.5	4.15	2.81	47.2	0.23	54.4	17.65	1.95	27.6	0.23	47.4

Operational phase emissions at archetype average dwelling level

Table 5.6 gives the archetype weighted average operational primary energy use for each life cycle phase for each scenario (see Equation 4.9). Results are broken down by Irish and non- Irish sources of energy. Overall, the study found the operational primary energy use by a weighted mean archetype to be 45,478kWh/yr for the BaseCase scenario, comprising 39,548kWh/yr and 5,930kWh/yr of national and international sources of energy, respectively. The proportion of national sources of energy (13%) represents the primary energy required for fuel supply chain processes that occurred abroad.

Table 5.6: Weighted mean primary energy (kWh/yr) results of the population of housing across life cycle phases and domestic and international sources

	BaseCase				Current Regulations				Passive House standard			
	National	International	Import %	Total	National	International	Import %	Total	National	International	Import %	Total
Retrofit	0	0	0	0	199	778	80	977	253	1,010	80	1,263
Maintenance	43	59	58	101	85	202	70	287	99	246	71	345
Operation	39,548	5,930	13	45,478	20,093	2,271	10	22,364	10,092	1,639	14	11,731
Disassembly	25	43	63	67	35	56	61	91	29	57	66	86
Total	39,615	6,031	13	45,646	20,412	3,306	14	23,719	10,473	2,952	22	13,425

Operational improvement potential at archetype average dwelling level

Table 5.6 also shows the relative improvement potential across retrofit options. As can be seen the result of the operational energy improvement potential is striking. For the Current regulation scenario, the operational phase primary energy reduced from 45,478 to 22,364kWh/yr (i.e. reduced by 51%) when compared to the BaseCase scenario.

This result agrees with findings from other studies for operational energy at archetype level and the work of Feist (1997) that the energy use by a conventional building is about twice that of a low-energy building, especially as there are similarities in the energy savings components used by this study and that of Feist (1997). For example, the work of Feist (1997) incorporates good insulation to envelope elements, reduced thermal bridges, air-tightness, low-energy windows and mechanical ventilation.

Similarly, for the Current Regulations scenario, the share (%) of international source of energy reduced from 13% to 10%. In addition to the characteristic figures of the Current Regulations scenario mentioned above, the reduction in the share of imports compared to the BaseCase scenario reflects significant reductions in imported fossil fuels.

On the other hand, the Passive House scenario presents greater improvement potential, as operational energy is reduced from 45,478 to 11,231kWh/yr (75%) compared to the BaseCase scenario. This is supported by Feist (1997) who found that the annual primary energy use of passive house buildings is around 18% of that required by conventional buildings.

It is found that retrofitting from BaseCase scenario to the Current Regulations results in 61.7% savings in the weighted average dwelling energy consumption attributable to international sources. Similarly, retrofitting the BaseCase house to the Current Regulations scenario represents savings of 72.4% of energy attributable to imported fossil fuels. Similarly, retrofitting from Current Regulations to Passive House standard scenario will result in 27.8% savings in energy attributable to imported fossil fuels relative to the Current Regulations scenario.

Unlike the case of the Current Regulations scenario discussed above, the share (%) of the international sources of energy increased from 13% to 14% for the Passive House scenario compared to the BaseCase scenario. This reflects the increased electricity usage including avoidance of delivered heat energy, and particular as the Irish electricity mix is still largely based on imported fossil fuels.

Similarly, Table 5.7 summarises weighted mean GHG emissions of retrofit scenarios. In comparison to Table 5.6, it can be seen that there is a correlation between energy consumption and GHG emissions is emphasised as the results table directly reflects those of the primary energy.

Table 5.7: Global warming potential ($kgCO_2/yr$) weighted mean results across domestic and non-domestic sources

	Base				Current Regulations				Passive House standard			
	National	International	Import %	Total	National	International	Import %	Total	National	International	Import %	Total
Retrofit	0	0	-	0	86	383	82	469	236	1,122	83	1,358
Maintenance	84	362	81.2	446	109	517	82.6	625	71	360	83.5	432
Operation	9,772	1,478	13	11,251	5,002	572	10	5,573	2,645	361	12	3,006
Disassembly	9.6	10.3	51.6	20	8.45	14.4	63	23	8.7	13.4	60.6	22
Total	9,866	1,851	16	11,716	5,205	1,486	22	6,691	2,961	1,857	39	4,818

Operational phase emissions at national stock level

Table 5.8 shows estimated national life cycle CO_2-eq emissions by archetype for each retrofit scenario. The operational phase primary energy-related emissions of all archetypes under the Base scenario were calculated using Equation 4.10. Estimated national housing stock emissions are summed by archetype and life cycle phase for each scenario. The result shows that the archetype stock model estimates residential sector total primary energy-related emissions of 9, 838ktCO_2-eq. in 2005. According to the Environmental Protection Agency of Ireland (EPA, 2011), the total end-use energy-related emissions recorded for the sector in 2005 was 7,282KtCO_2-eq. The difference between the estimated and recorded figures can be explained by the fact that national statistics figure only recorded domestic emissions (EPA, 2011) and excluded some life cycle phases. Estimated figures account for non-domestic emissions and all life cycle stages. The study figure of 9,447ktCO_2-eq. is therefore found to be generally consistent with national statistics.

When further viewed relative to total stock emissions, the following observations can be inferred from the results of the BaseCase scenario:

- Detached houses account for 68.7% of the national stock emissions. Semi-detached house/end-terraced house archetypes are responsible for 16.0% of the total emissions. Mid-terraced house/apartment archetypes represent 15.3% of the total national stock emissions.
- When compared to the number of houses, semi-detached house/end-terraced house archetypes and mid-terraced house/apartment archetypes represent a lower share of the emissions than the share of the number of houses would suggest (27.6% and 23% of the total number of houses in the stock of housing, respectively) (see Figure 5.4 below).

These observations mirror the lower emissions of semi-detached house/end-terraced house and mid-terraced house/apartment archetypes (except for archetype 13) per m^2 floor area when compared to the detached house archetypes.

Table 5.8: National life cycle CO_2-eq (ktCO_2-eq/yr) emissions by archetype for each retrofit scenario

		BaseCase					Current Regulations					Passive House standard				
Dwelling type	Archetype reference	Retrofit	Maintenance	Operation	Disassembly	Total	Retrofit	Maintenance	Operation	Disassembly	Total	Retrofit	Maintenance	Operation	Disassembly	Total
Detached house archetype	1	0	91.7	2,327	3.9	2,422	95.0	129.3	1,118	4.5	1,347	225	121	607	4.7	958
	2	0	24.3	1,443	2.2	1,470	50.0	32.0	674	2.5	758	118	31	319	2.5	470
	3	0	12.1	868	1.2	882	25.1	15.9	303	1.3	345	59	11	159	1.3	231
	4	0	31.7	849	1.4	882	32.0	44.8	389	1.6	467	77	25	214	1.7	317
	5	0	24.1	636	1.0	661	27.5	33.8	292	1.2	354	61	19	158	1.2	240
	6	0	15.9	364	0.7	380	17.4	22.5	194	1.9	236	40	12	106	0.8	159
Sub-total		0	200	6,487	10	6,697	247	278	2,969	13	3,507	581	219	1,563	12	2,375
Semi-detached house /end-terraced house archetypes	7	0	24.3	380	0.8	405	25.3	34.7	301	1.1	362	60	19	164	1.1	244
	8	0	12.2	190	0.4	202	9.2	17.2	108	0.4	135	27	9	59	0.4	96
	9	0	12.2	190	0.4	202	9.2	17.2	108	0.4	135	27	16	59	0.4	102
	10	0	48.6	759	1.6	810	36.9	68.9	432	1.5	539	106	38	235	1.5	381
Sub-total		0	97	1,519	3.21	1,619	81	138	949	3.29	1,171	220	83	517	3.43	823
Mid-terraced house/apartment archetypes	11	0	50.3	723	1.8	775	37.4	71.5	428	1.5	539	200	39	250	1.6	491
	12	0	19.0	283	0.7	303	14.1	26.9	161	0.6	203	75	15	94	0.6	185
	13	0	7.7	436	0.8	444	15.1	10.2	171	0.8	197	64	7	100	0.8	172
Sub-total		0	77	1,442	3.19	1,552	67	109	761	2.95	939	339	61	445	3.05	848
Total across life cycle phases		0	374	9,447	17	9,838	394	525	4,680	19	5,618	1,140	362	2,524	19	4,045
Stock total across different options		9,838					5,618					4,045				

Operational phase improvement potential at national stock level

Table 5.8 shows the relative operational improvement potential at national stock level across retrofit scenarios. It can be seen that for Current Regulations standard the improvement potential is significant. Detached houses have the highest emissions reduction potential; upgrading them to the Current Regulations scenario would reduce operational emissions from 6,487ktCO_2-eq/yr to 2,969ktCO_2-eq/yr (54%). A major factor for explaining the significant potential for emissions reduction in detached house archetypes is its share of national stock.

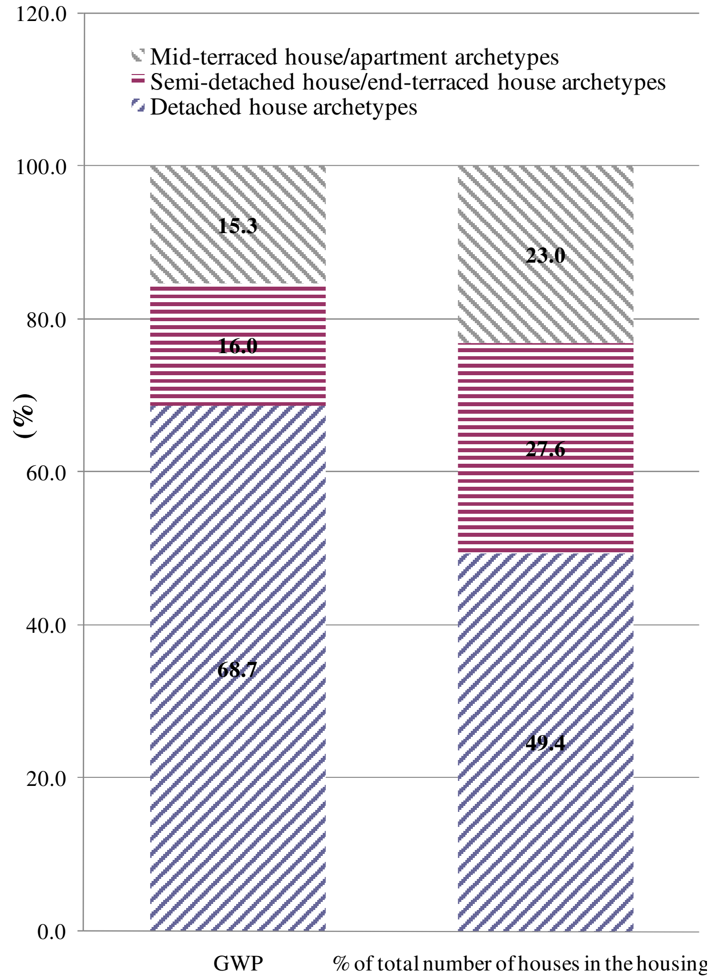

Figure 5.4: Relative contribution (%) of operational emissions across dwelling type at national stock level

Semi-detached house/end-terraced house archetypes recorded the lowest emission reduction, as operational emissions were reduced from 1,519ktCO_2-eq/yr to 949ktCO_2-eq/yr (38%). For the mid-terraced house/apartment archetypes, operational emissions reduced from 1,442ktCO_2-eq/yr to 761ktCO_2-eq/yr (47%). When estimated national housing stock operational emissions are summed by archetype for each scenario, operational emission reductions for the Current Regulations scenario were found to be 3,829ktCO_2-eq/yr (40%), as operational emissions reduced from 9,447ktCO_2-eq/yr to 5,618ktCO_2-eq/yr.

Operational emissions savings are greater for the Passive House than the Current Regulations scenario. Detached house archetypes display the highest operational emissions savings reductions under the Passive House scenario, decreasing from 6,487ktCO_2-eq/yr to 1,563ktCO_2-eq/yr (76%). Semi-detached house/end-terraced house archetypes recorded the lowest emission reduction, as operational emissions reduced from 1,519ktCO_2-eq/yr to 517ktCO_2-eq/yr (66%). For the mid-terraced house/apartment archetypes, operational emissions decreased from 1,442ktCO_2-eq/yr to 445ktCO_2-eq/yr (69%). When estimated national housing stock operational emissions are summed by archetype for each scenario, operational emission reductions for the Passive House scenario were found to be 5,402ktCO_2-eq/yr (57%), as operational emissions reduced from 9,447ktCO_2-eq/yr to 4,045ktCO_2-eq/yr.

The results of the operational phase at national stock level above also support study earlier findings for operational emissions both at archetype and average dwelling levels.

When the results of both Current Regulations scenario and Passive House scenario are compared, the national operational emissions in the Current Regulations scenario reduced from 4,680ktCO_2-eq/yr to 2,524ktCO_2-eq/yr, representing savings of 46%. Detached houses display the the highest operational national emissions savings for the Passive House scenario relative to Current Regulations scenario, representing 47.4%. This is followed by mid-terraced house/apartment (41.5%) and semi-detached house/end-terraced house (45.5%), respectively.

5.3.2 Retrofit phase

Tables 5.5, 5.7 and 5.8 indicate the results of the retrofit phase emissions at archetype, archetype average dwelling and archetype national stock levels for the different scenarios. The BaseCase scenario has no impacts for the retrofit phase as it was not renovated.

Retrofit phase emissions at archetype level

Table 5.5 indicates the results of retrofit phase emissions at archetype level for the different scenarios. For all archetypes within the Current Regulations scenario, the emissions of the retrofit phase ranged from 6.6% - 7.8% of the life cycle's total. Detached house archetypes indicate higher emissions for the retrofit phase (4.39kgCO_2-eq/m^2.yr – 4.9kgCO_2-eq/m^2.yr) compared to semi-detached house/end-terraced house archetypes (3.2 – 4.8kgCO_2-eq/m^2.yr) and (3.1- 4.15kgCO_2-eq/m^2.yr) mid-terraced house/apartment archetypes. All of the above trends result from the use of energy savings components to bring the Basecase scenario to the thermal level of the Current Regulations scenario.

For all archetypes within the Passive House scenario, the emissions of the retrofit phase ranged from 23.5% - 40.8% of life cycle's total. Mid-terraced house/apartment archetypes have higher emissions (16.6 – 17.6kgCO_2-eq/m^2.yr) compared to detached house archetypes (10.3 – 10.9kgCO_2-eq/m^2.yr) and semi-detached house/end-terraced house archetypes (9.1 – 10.4kgCO_2-eq/m^2.yr).

Retrofit phase emissions at average dwelling level

Table 5.7 indicates the weighted mean archetype emissions of the retrofit phase across domestic and non-Irish sources for the different scenarios. For the Current Regulations scenario, the retrofit phase emissions were estimated to be 469kgCO_2-eq/yr, using Equation 4.9. When viewed according to national and international sources of emissions, 82% of these emissions were international. This significant result can be explained due to increased embodied retrofit emissions resulting from the use of energy savings components in retrofitting the BaseCase scenario to attain the thermal level of the Current Regulations scenario.

Similarly, the Passive House scenario recorded a significant retrofit phase emissions, representing 1,358kgCO_2-eq/yr. When viewed according to national and international sources of emissions, 83% of these emissions were from international sources. This share is higher than for the Current Regulations scenario due to greater use of energy savings components.

The result of the comparison between Current Regulations scenario and Passive House scenario is striking as retrofitting emissions increased from 469kgCO_2-eq/yr to 1,358kgCO_2-eq/yr. This reflects the increased use of insulation materials and other retrofitting components to further reduce operation emissions. The result further suggests that retrofitting from Current Regulations scenario to Passive House scenario presents approximately 66% increases in emissions attributable to the use of energy savings components.

Retrofit phase emissions at national stock level

Table 5.8 shows estimated national retrofit life cycle CO_2-eq emissions by archetype for each retrofit scenario. The retrofit phase emissions of all archetypes under the Current Regulations and Passive House standard scenarios were calculated using Equation 4.10. The result shows that the archetype stock model estimates the Current Regulations and Passive House standard scenarios emissions to be 394ktCO_2-eq and 1,140ktCO_2-eq, respectively. Detached house archetypes display the highest retrofit phase emissions under the Current Regulations scenario, representing 247ktCO_2-eq (63%) of national stock total for the scenario. This is followed by semi-detached house/end-terraced house archetypes; and mid-terraced house/apartment archetypes recording retrofit emissions of

81ktCO_2-eq (20%) and 67ktCO_2-eq (17%), respectively. Similarly, within the Passive House scenario, detached house archetypes shows the highest retrofit phase emissions, representing 581ktCO_2-eq (51%) of national stock total for the scenario. Both semi-detached house/end-terraced house archetypes; and mid-terraced house/apartment archetypes recorded retrofit emissions of 220ktCO_2-eq (19%) and 339ktCO_2-eq (30%), respectively.

A comparison between Passive House and Current Regulations standards shows that retrofit emissions increased from 394ktCO_2-eq to 1,140ktCO_2-eq when compared with the Current Regulations standard. This result represents 65% increases in national retrofit emissions attributable to the increased use of energy savings components.

In addition to some of the reasons earlier given in support of the results at archetype level, all of the above findings are resulting from share of building stock of the respective archetype dwelling types for the two retrofit scenarios.

5.3.3 Maintenance phase emissions at archetype level

Table 5.5 indicates the results of maintenance phase emissions at archetype level for the different scenarios. For a majority of archetypes and the different house scenarios, the maintenance phase does not exceed 16% of the life cycle's total. Although, maintenance phase in the BaseCase scenario is of minor relevance, the significance of the phase increases with retrofitting of the BaseCase scenario. Results of the BaseCase scenario show that maintenance phase emissions ranged from 2.13 – 4.3 kgCO_2-eq/m^2.yr or (1.4% - 6.5%) of the life cycle's total.

In the Current Regulations scenario, the importance of the maintenance phase increased significantly as the phase's emissions ranged from 2.81 – 6.03kgCO_2-eq/m^2.yr or (4.2% - 13.3%) of the life cycle's total compared to the BaseCase scenario. This finding is mainly a result of scheduled regular maintenance activities and replacement materials and components at the end of their service lives.

For the Passive House standard scenario, results indicate greater importance for the maintenance phase as the phase's emissions ranged from 1.95 – 5.58 $kgCO_2$-eq/m^2.yr or (4.1% - 15.9%) of the life cycle's total compared to the BaseCase scenario. This is explained by greater replacement of materials and components at the end of their service lives, especially as the scenario undertakes more energy saving components required to be replaced at the end of their service lives.

Maintenance phase emissions at archetype average dwelling level

Table 5.7 shows the weighted mean maintenance phase emissions for each life cycle phase for each scenario (see Equation 4.9). Results were broken down by national and international sources of emissions. Overall, the study found the maintenance emissions by a weighted mean archetype for the BaseCase scenario to be 446$kgCO_2$-eq/yr, comprising 84$kgCO_2$-eq/yr and 362$kgCO_2$-eq/yr of national and international sources of emissions, respectively. The proportion of international sources (81.2%) represents the emissions associated with imported materials required for scheduled maintenance of the building throughout its service lives.

Retrofitting to Current Regulations scenario resulted in significant increases in emissions of maintenance phase compared to the BaseCase scenario. Maintenance phase emissions for the Current Regulations scenario was estimated to be 625$kgCO_2$-eq/yr, comprising 109$kgCO_2$-eq/yr and 517$kgCO_2$-eq/yr of national and international sources of emissions, respectively. The proportion of international sources (82.6%) is found to be slightly higher than for the BaseCase scenario and represents the emissions associated with imported materials required for scheduled maintenance and replacement of materials and components of retrofitting at the end of their service lives.

On the other hand, retrofitting to Passive House scenario resulted in marginal increases in emissions of maintenance phase compared to the BaseCase scenario. This can be explained by the avoidance of regular (every 16 years) (EST 2006, 2007) replacement of oil and gas-fired boilers, especially oil-fired boiler noted for its high energy intensity in its production. For the Passive House scenario, maintenance phase emissions was estimated to be 432kgCO_2-eq/yr, comprising 71kgCO_2-eq/yr and 360kgCO_2-eq/yr of national and international sources of emissions, respectively. The share of international sources (83.5%) is found to be higher than for the BaseCase scenario and represents the emissions associated with imported materials required for scheduled maintenance as well as greater number of materials and components of retrofitting required to be replaced at the end of their service lives.

Maintenance phase emissions at national stock level

Table 5.8 shows estimated national life cycle CO_2-eq emissions by archetype for each house scenario. Maintenance phase emissions for the BaseCase scenario was estimated to be 374kgCO_2-eq/yr, comprising 200kgCO_2-eq/yr (53%), 97kgCO_2-eq/yr (26%) and 77kgCO_2-eq/yr (21%) for detached house, semi-detached house/end-terraced house archetypes and mid-terraced house/apartment archetype dwellings, respectively.

Current Regulations scenario displays the highest national maintenance emissions of 525kgCO_2-eq/yr, comprising 278kgCO_2-eq/yr (53%), 138kgCO_2-eq/yr (26%) and 109kgCO_2-eq/yr (21%) for detached house, semi-detached house/end-terraced house archetypes and mid-terraced house/apartment archetype dwellings, respectively.

Maintenance phase emissions for the Passive House scenario is the lowest and was estimated to be 362kgCO_2-eq/yr, comprising 219kgCO_2-eq/yr (60%), 83kgCO_2-eq/yr (23%) and 61kgCO_2-eq/yr (17%) for detached house, semi-detached house/end-terraced house archetypes and mid-terraced house/apartment archetype dwellings, respectively. Passive House scenario recorded the lowest maintenance emissions because of those reasons earlier given at archetype average dwelling level.

In addition to some of the reasons earlier given in support of the results at archetype level, all of the above findings are resulting from share of building stock of the respective archetype dwelling types.

5.3.4 Disassembly phase emissions at archetype level

Table 5.5 shows the results of disassembly phase emissions at archetype level. The disassembly phase is of little significance for all archetypes and for the different house scenarios. For the BaseCase scenario, results show that the disassembly phase does not exceed 0.2% of the life cycle's total. This can be explained as the phase incorporates mainly embodied emissions required for detaching reusable materials, demolition of the building and transporting all materials to recyclers at disassembly including all associated services.

Scheuer et al., (2003) found the energy required for building demolition and transportation of construction and demolition waste to be 0.2% of the life cycle's total energy. This supports the results presented in Table 5.3.

However, it should be noted that the significance of the disassembly phase increases with retrofitting and maintenance of the BaseCase scenario. In all archetypes for the Current Regulations scenario, the maintenance phase does not exceed 0.51% of the life cycle's total. The disassembly phase higher share of the life cycle total emissions in the

Current Regulations scenario compared to the BaseCase scenario can be explained by the increased materials of disassembly associated with the use of energy saving components including greater uptake of maintenance materials, all of which are required to be detached and transported to recyclers at disassembly.

Passive House scenario shows the highest share of disassembly phase emissions relative to the life cycle total. In all archetypes for the Passive House scenario, disassembly phase does not exceed 0.9% of the life cycle total. This reflects greater use of energy saving components and of maintenance, all of which are required to be detached and transported to recyclers.

Table 5.9: Share (%) disassembly phase emissions relative to life cycle emissions total

Archetype		Scenario		
Dwelling type	Reference	BaseCase	Current Regulations	Passive House
Detached house	1	0.14	0.38	0.58
	2	0.13	0.45	0.88
	3	0.13	0.51	0.87
	4	0.13	0.37	0.63
	5	0.14	0.39	0.62
	6	0.16	0.38	0.62
Semi-detached house/end-terraced house	7	0.17	0.32	0.54
	8	0.17	0.32	0.54
	9	0.17	0.32	0.54
	10	0.17	0.32	0.54
Mid-terraced house/apartment archetype dwellings	11	0.16	0.32	0.54
	12	0.17	0.33	0.53
	13	0.16	0.47	0.91

Disassembly phase at archetype average dwelling level

Table 5.7 gives the weighted mean disassembly phase emissions for each life cycle phase for each scenario. Overall, the study found the disassembly emissions by a weighted mean archetype for the BaseCase scenario to be 20kgCO_2-eq/yr, comprising 9.6kgCO_2-eq/yr and 10.3kgCO_2-eq/yr of national and international sources of emissions, respectively. The proportion of international sources (51.6%) represents the emissions associated with upstream production activities for electricity required for crane lifting and diesel for transportation of disassembly.

Retrofitting to Current Regulations scenario resulted in 15% increase in emissions of disassembly phase compared to the BaseCase scenario due to the additional materials and components including the cost of refurbishment services required during disassembly for the progressive increases in materials and components of maintenance and retrofitting as the age of the building increases. Maintenance phase emissions for the Current Regulations scenario was estimated to be 23kgCO_2-eq/yr, comprising 8.45kgCO_2-eq/yr and 14.4kgCO_2-eq/yr of national and international sources of emissions, respectively. The proportion of international sources (63%) is found to be higher than for the BaseCase due to reason earlier given above.

Similarly, retrofitting to Passive House scenario resulted in 10% increase in emissions of disassembly phase compared to the BaseCase scenario. This can be explained by the avoidance of regular (every 16 years) (EST 2006, 2007) replacement of oil and gas-fired boilers, especially oil-fired boiler noted for its higher mass, especially when compared to gas/condensing instantaneous water heating boiler. It should be noted that the BaseCase scenario runs on an oil-fired boiler whilst the Current Regulations scenario has a condensing instantaneous water heating boiler. For the Passive House scenario, maintenance phase emissions were estimated to be 22kgCO_2-eq/yr, comprising 8.7kgCO_2-eq/yr and 13.4kgCO_2-eq/yr of national and international sources of emissions, respectively. The share of international sources (60.6%) is found to be higher than for the BaseCase scenario, mainly a result of the earlier discussion above.

Disassembly phase emissions at national stock level

Table 5.8 gives estimated national disassembly life cycle CO_2-eq emissions by archetype for each house scenario. The result shows that the archetype stock model estimates the BaseCase, Current Regulations and Passive House standard scenarios emissions to be 17ktCO_2-eq., 19ktCO_2-eq and 19ktCO_2-eq, respectively. Detached house archetypes display the highest disassembly phase emissions under the BaseCase scenario, representing 10ktCO_2-eq (62%) of national stock total for the scenario. This is followed by semi-detached house/end-terraced house archetypes; and mid-terraced house/apartment archetypes recording retrofit emissions of 3.21ktCO_2-eq (19%) and 3.19ktCO_2-eq (19%), respectively.

For the Current Regulations scenario, detached house shows the highest disassembly phase emissions, representing 13ktCO_2-eq (68%) of national stock total for the scenario. Semi-detached house/end-terraced house disassembly emissions were estimated to be 3.29ktCO_2-eq (17%). The lowest disassembly emissions for this scenario were recorded by mid-terraced house/apartment archetypes, representing 2.95ktCO_2-eq (15%).

Similarly, within the Passive House scenario, detached house archetypes displays the highest disassembly phase emissions, representing 12ktCO_2-eq (66%) of national stock total for the scenario. Semi-detached house/end-terraced house disassembly phase emissions were estimated to be 3.43ktCO_2-eq (18%). mid-terraced house/apartment archetypes recorded the lowest disassembly phase emissions of 3.05ktCO_2-eq (16%), respectively.

5.3.5 Life cycle energy and emissions

Figures 5.5 and 5.6, and Tables 5.6 and 5.7, indicate the results of the life cycle energy and emissions at archetype and archetype average dwelling levels for the different scenarios. Similarly, Figures 5.7 and 5.8 indicate the results of the national housing stock life cycle emissions for the different scenarios. This section accounts for the life cycle energy results across the above levels.

Life cycle energy at archetype level

Figure 5.5 indicates the results of life cycle primary energy at archetype level for each scenario. Overall, life cycle primary energy use at archetype level for the BaseCase scenario ranges from: 386kWh/m^2.yr – 614kWh/m^2.yr for detached house archetypes, 272kWh/m^2.yr for semi-detached house/end-terraced house archetypes, and 250kWh/m^2.yr – 501kWh/m^2.yr for mid-terraced house/apartment archetypes.

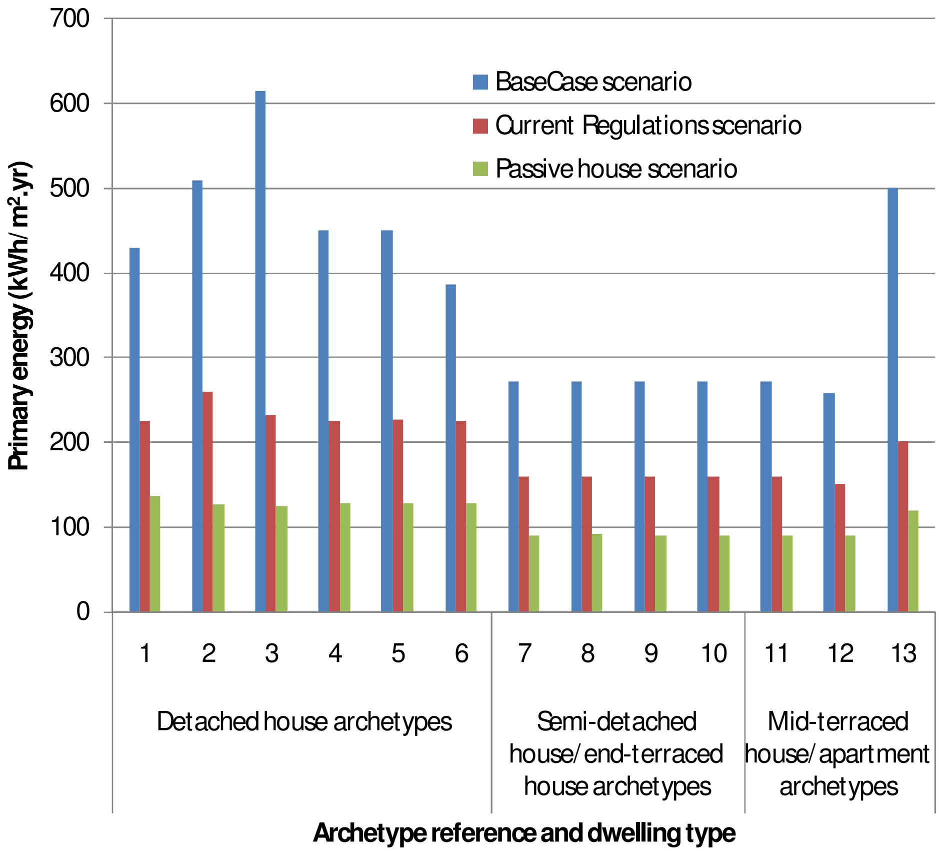

Figure 5.5: Life cycle primary energy of all archetypes for all scenarios

The above results are found to correspond with findings in the literature. Ramesh et al., (2010) reviewed the results of life cycle analyses of 46 residential case studies (most of which are from cold countries) from 13 countries. They calculated and normalised the results of these studies to kWh/m^2.yr in order to remove the dissimilarities in parameters such as expression of results in end-use or primary energy, floor area and service life. Results indicate that the life cycle primary energy requirement of conventional residential buildings falls within the range of 150kWh/m^2.yr - 400kWh/m^2.yr. The difference between the above results and that of present study can be explained as the reported studies did not include life cycle primary energy for fuel supply chain processes that occurred abroad. It should also be noted that a conventional building is characterised by construction practice reminiscent of its period of construction.

In another study, Sartori and Hestnes, (2006) reviewed the results of life cycle analyses of 60 residential case studies (most of which are from cold countries) from 13 countries in order to clarify the relative importance of operating and embodied energy of low energy buildings. They also calculated and normalised the results of these studies to kWh/m^2.yr in order to remove the dissimilarities in parameters such as expression of results in end-use or primary energy, floor area and service life. Results indicate that the life cycle primary energy requirement of conventional residential buildings falls within the range of 250kWh/m^2.yr - 550kWh/m^2.yr. The same reason as given above explains the difference between the above results and that of this study. All of the above results support the study results in Figure 5.5.

All retrofit scenarios yield significant life cycle primary energy improvement compared to the BaseCase scenario. Overall, and for most archetypes the life cycle primary energy reduced by at least 41% and 69% for the Current Regulations and Passive House standard scenarios, respectively compared to the BaseCase scenario. Similarly, a comparison of the Passive House scenario relative to the Current Regulations scenario indicates that for a majority of archetypes the life cycle primary energy reduced by at least 39%. Detached house under the Current Regulations scenario displays the highest range of primary life cycle energy use, representing 225 - 261kWh/m^2.yr. Mid-terraced house/apartment archetypes life cycle primary energy ranges from 151 - 201kWh/m^2.yr. Semi-detached house/end-terraced houses recorded the lowest life cycle primary energy of 160kWh/m^2.yr.

All of the above findings are resulting from those reasons earlier given in support of the results at life cycle phase level.

When compared with literature, the results of life cycle primary energy use at archetype level in the Current Regulations scenario are found to be generally consistent with literature. Sartori and Hestnes, (2006) indicates that for low energy buildings, life cycle primary energy requirement falls within the range of 50-210kWh/m^2.yr.

Within the Passive House scenario, detached house shows the highest range of life cycle primary energy, representing 126 – 137kWh/m^2.yr, followed by mid-terraced house/apartment archetypes and semi-detached house/end-terraced house, representing 90 – 120kWh/m^2.yr and 90kWh/m^2.yr, respectively.

Winther and Hestnes (1999) analysed embodied energy and operational energy of a Norwegian row house and compared the "As is" building with four other standards including a passive house standard option. Results show that the Passive House scenario used around 150kWh/m^2.yr. This result is within the range of the results of the Passive House scenario in Figure 5.5.

Similarly, Figure 5.6 indicates global warming potential (kgCO_2-eq) for all archetypes for all house scenarios. The direct correlation between resource consumption and GHG emissions is emphasized as this Figure directly reflects that of the primary energy. These results represent the outputs from GaBi 4.4 LCA software for primary energy-related life cycle emissions of all archetypes for all house scenarios. Overall, life cycle emissions at archetype level for the BaseCase scenario range from: 101.7 – 157.2kgCO_2-eq/m^2/yr for detached houses, 69.9kgCO_2-eq/m^2/yr for semi-detached house/end-terraced house archetypes, and 64.2 – 122.5kgCO_2-eq/m^2/yr for mid-terraced house/apartment archetypes. The higher emissions by detached houses compared to the other two dwelling types can be explained by those reasons earlier given in the case of the results of primary energy.

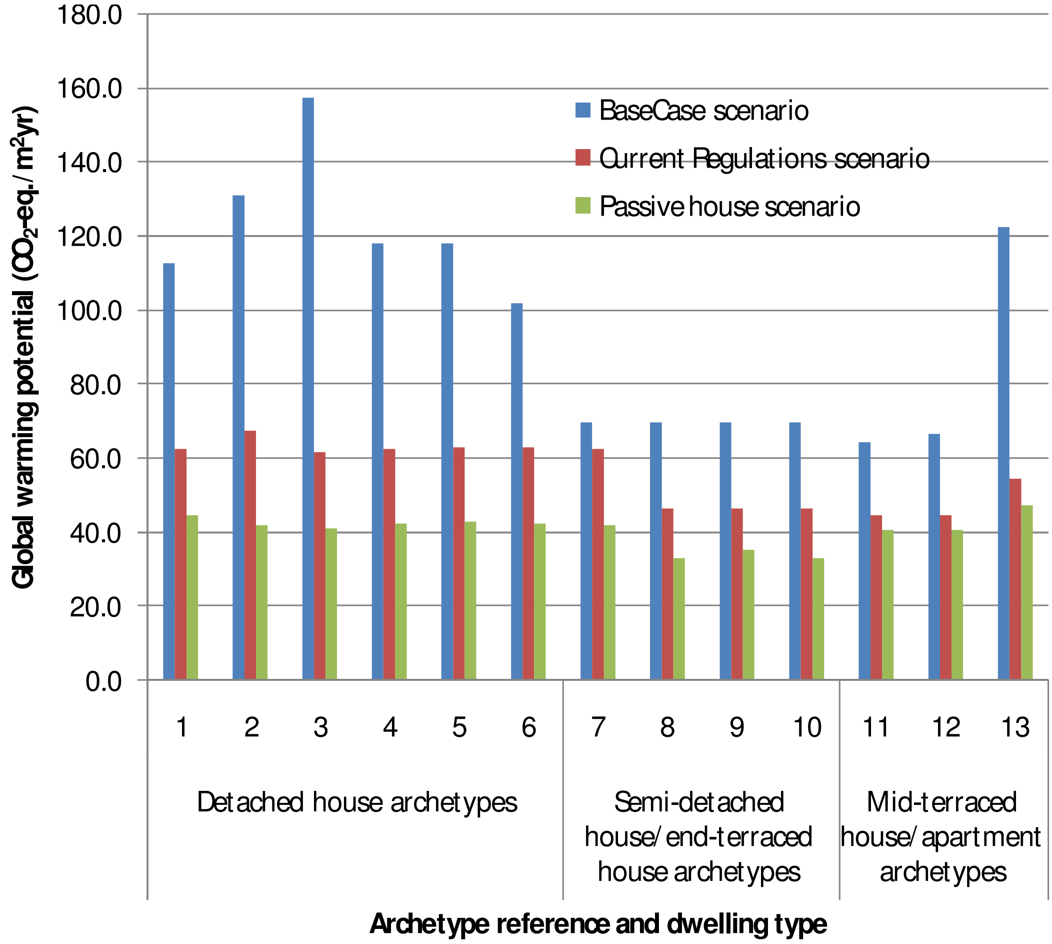

Figure 5.6: Life cycle primary energy-related emissions of all archetypes for all scenarios

Life cycle energy at archetype average dwelling level

Table 5.6 shows the weighted mean life cycle energy for each scenario. Similar to the other weighted means phase's findings, results were broken down by national and international sources of primary energy. Overall, the study found the life cycle primary energy by a weighted mean archetype for the BaseCase scenario to be 45,646kWh/yr, out of which 6,031kWh/yr (13%) was estimated for the international sources of primary energy. Those reasons that explain the proportion of national and international sources of energy at life cycle phase level for the BaseCase scenario above are also applicable to the weighted mean archetype.

All retrofit scenarios yield significant life cycle weighted mean primary energy improvement compared to the BaseCase scenario. Retrofitting to the Current Regulations scenario resulted in 48% savings as life cycle primary energy reduced from 45,646kWh/yr to 23,719kWh/yr out of which 3,306kWh/yr or 14% is estimated for international sources of energy.

Similarly, retrofitting to Passive House scenario relative to BaseCase resulted in 71% reduction as life cycle primary energy reduced from 45,646kWh/yr to 13,425kWh/yr out of which 2,952kWh/yr or 22% is estimated for international sources of energy. In addition, a comparison between Current Regulations and Passive House standard scenarios indicates for most dwellings at least 43.4% weighted mean life cycle energy savings relative to the Current Regulations scenario.

Likewise, Table 5.7 shows the weighted mean life cycle global warming potential (kgCO_2-eq) for all house scenarios. The direct correlation between resource consumption and GHG emissions is emphasized as this table directly reflects that of the primary energy. These results represent the outputs from GaBi 4.4 LCA software for primary energy-related emissions of the average archetype dwelling for all house scenarios.

Life cycle emissions results at archetype national stock level

Figure 5.7 shows estimated national life cycle CO_2-eq emissions by archetype for each house scenario. The result shows that the archetype stock model estimates national life cycle emissions for the BaseCase, Current Regulations and Passive House standard scenarios to be 9,838ktCO_2-eq., 5,618ktCO_2-eq and 4,045ktCO_2-eq, respectively. Detached house under the BaseCase scenario displays the highest life cycle national emissions of 6,697ktCO_2-eq or 68% of national stock emissions. Semi-detached house/end-terraced house archetypes are responsible for 1,619ktCO_2-eq or 16.5% of the total emissions. Mid-terraced house/apartment archetypes represent 1,552ktCO_2-eq 15.5% of national stock emissions.

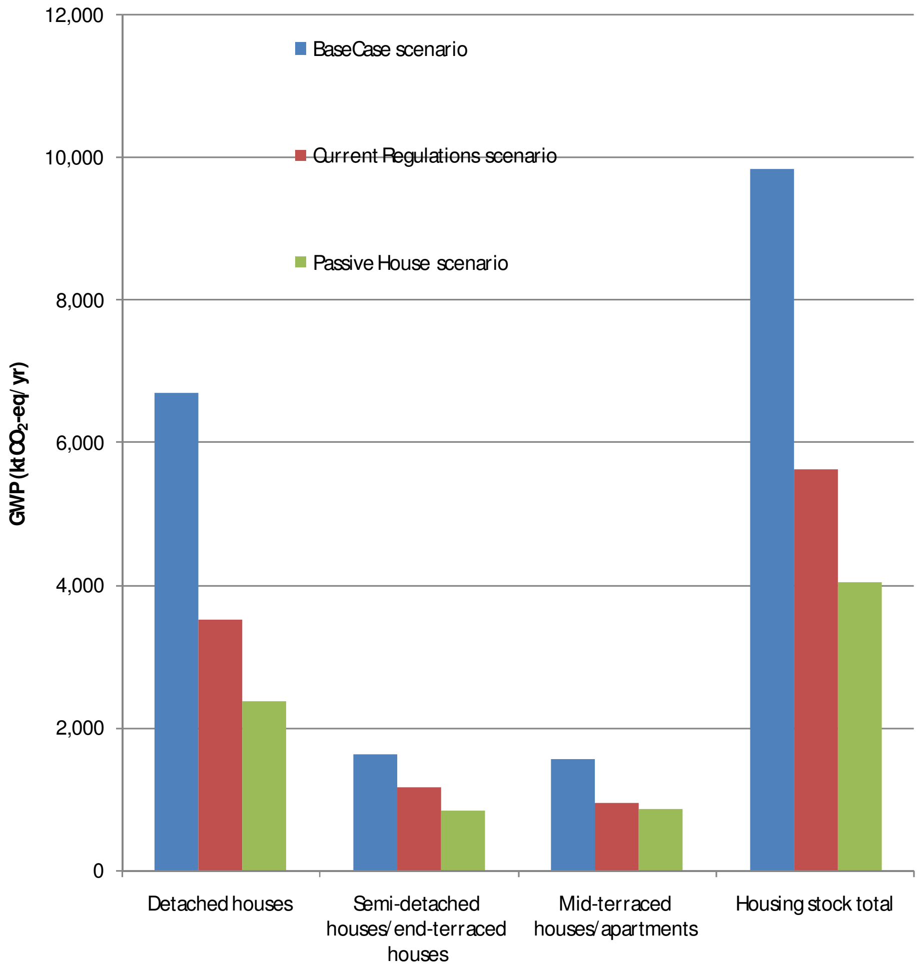

Figure 5.7: Life cycle annual environmental impact of the existing Irish housing stock for the environmental impact category "global warming potential"

It can be seen from the above that all retrofit scenarios resulted in significant life cycle emissions reductions as emissions of the Current Regulations and Passive House scenarios resulted in 43% and 59% savings, respectively. Detached houses have the highest emissions reduction potential; upgrading these to Current Regulations scenario would reduce national life cycle emissions from 6,697ktCO_2-eq in the BaseCase scenario to 3,507ktCO_2-eq (48%). For semi-detached house/end-terraced house archetypes, national life cycle emissions reduced from 1,619ktCO_2-eq in the BaseCase scenario to 1,171ktCO_2-eq (27.7%). Mid-terraced house/apartment archetypes recorded the lowest emissions reductions, as national life cycle emissions were reduced form 1,552ktCO_2-eq in the BaseCase scenario to 939ktCO_2-eq (39.5%).

Life cycle emissions savings are greater for the Passive House than for the Current Regulations scenario. Detached house archetypes show the highest life cycle national emissions savings under the Passive House scenario, deceasing from 6,697ktCO_2-eq in the BaseCase scenario to 2,375ktCO_2-eq (65%). Semi-detached house/end-terraced house archetypes recorded the lowest emission reduction as life cycle emissions reduced from 1,619ktCO_2-eq in the BaseCase scenario to 823ktCO_2-eq (49%). For the mid-terraced house/apartment archetypes, life cycle emissions decreased from 1,552ktCO_2-eq in the BaseCase scenario to 848ktCO_2-eq.

A comparison of the Current Regulations scenario with the Passive House scenario indicates the detached house archetypes show the highest life cycle national emissions savings, as national emissions decreasing from 3,507ktCO_2-eq in the Current Regulations scenario to 2,375ktCO_2-eq (32%). Semi-detached house/end-terraced house archetypes recorded the lowest emission reduction as life cycle emissions reduced from 1,171ktCO_2-eq in the Current Regulations scenario to 823ktCO_2-eq (29.7%). For the mid-terraced house/apartment archetypes, life cycle emissions decreased from 939ktCO_2-eq in the Current Regulations scenario to 848ktCO_2-eq (9.7%).

The above findings are resulting from those reasons earlier discussed at archetype level for each scenario.

Total life cycle emissions at national stock level during a lifetime of 50 years

This section accounts for the total life cycle emissions at national stock level during a lifetime of 50 years.

Figure 5.8: shows estimated national lifetime CO_2-eq emissions by scenario. The lifetime emissions under the BaseCase scenario were calculated using Equation 4.11. Estimated national housing stock emissions are summed by archetype and life cycle phase for each scenario. The results shows residential sector total lifetime emissions to be 491.9MtCO_2-eq for the BaseCase scenario. Detached house archetypes show the highest lifetime emissions, representing 334.8MtCO_2-eq (68%). Semi-detached house/end-terraced house archetypes recorded a total of 81.08MtCO_2-eq (16.5%) lifetime emissions. Mid-terraced house/apartment archetypes recorded the lowest life cycle emissions, representing 76.1MtCO_2-eq (15.5%). Similar to the case of life cycle emissions at national level, the above findings are resulting from those reasons earlier given at life cycle level for the BaseCase scenario.

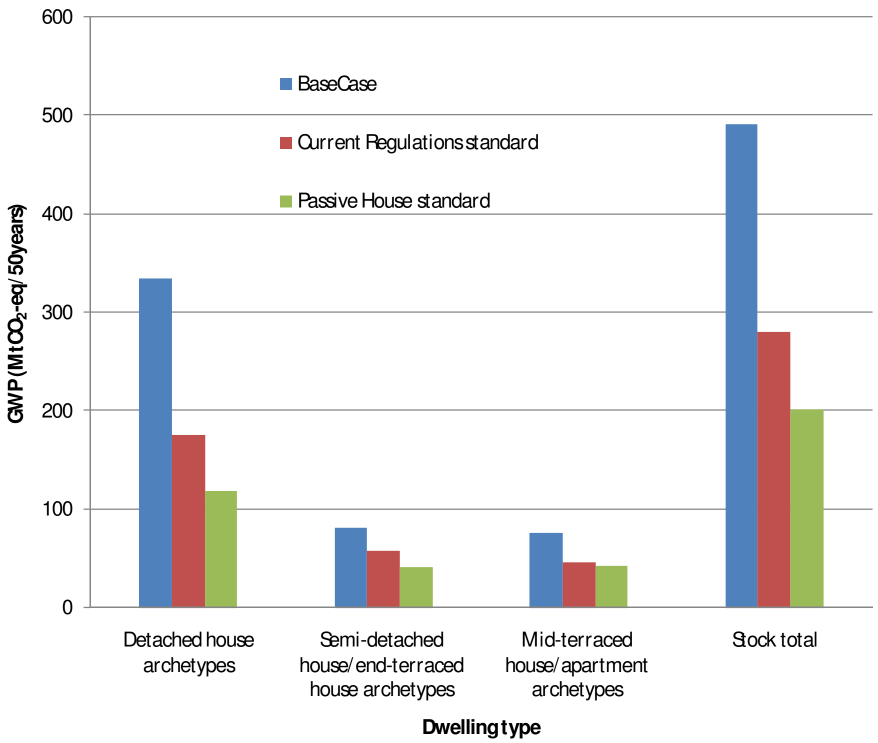

Figure 5.8: Lifetime life cycle environmental impact of the existing Irish housing stock for the environmental impact category “global warming potential”

For the Current Regulations scenario, lifetime emissions reduced by 43% compared to the BaseCase scenario, as lifetime emissions reduced from 491.9MtCO_2-eq to 280.9MtCO_2-eq. The estimated figure of 280.9MtCO_2-eq comprises 175.4 MtCO_2-eq, 58.6MtCO_2-eq and 47.0MtCO_2-eq lifetime emissions for detached house archetypes, semi-detached house/end-terraced house archetypes and mid-terraced house/apartment archetypes, respectively.

Significant emissions savings of approximately 59% were recorded for the Passive House scenario, as lifetime emissions reduced from 491.9MtCO_2-eq to 202.3MtCO_2-eq compared to the BaseCase scenario. Detached house archetypes displays the highest lifetime emissions savings (65%) under the Passive House scenario, decreasing from 334.8MtCO_2-eq to 118.7MtCO_2-eq. For the mid-terraced house/apartment archetypes, lifetime emissions deceased from 81.0MtCO_2-eq to 41.1MtCO_2-eq, representing savings of approximately (49%). Semi-detached house/end-terraced house archetypes recorded the lowest savings (44%) as lifetime emissions reduced from 76.1MtCO_2-eq to 42.4MtCO_2-eq.

A comparison between Current Regulations and Passive House standards shows that lifetime emission savings represent 28% compared to the Current Regulations scenario. Detached house archetypes displays the highest lifetime emissions savings, representing 32%. This is followed by mid-terraced house/apartment archetypes and Semi-detached house/end-terraced house archetypes with corresponding savings of 30% and 9.8%, respectively.

5.3.6 Cumulative embodied energy

In the context of the built environment embodied energy is defined as the sum of all the energy required in material extraction/mining, refinement, processing, fabrication, installation onsite and disassembly of the building including all associated transportation. Thus, the embodied energy in this study is the cumulative energy used across all life cycle phases except the operational phase. Table 5.10 illustrates the cumulative embodied energy contribution of all dwellings relative to life cycle total energy for all scenarios. Overall the percentage of the cumulative embodied energy at archetype level for the BaseCase scenario ranges from 0.24% - 0.47%. All retrofit scenarios resulted in cumulative embodied energy increases as the corresponding values for the Current Standard and Passive House scenarios are 4.8% - 7.0% and 10.3% – 14.75%, respectively. All of these are resulting from those reasons earlier discussed for the retrofit, maintenance and disassembly phases at archetype level in Sections 5.2.2, 5.2.3 and 5.2.4, respectively.

Table 5.10: Cumulative embodied energy (%) relative to life cycle energy at archetype level for all scenarios

		BaseCase scenario	Current Regulations scenario	Passive House scenario
Dwelling type	Archetype reference	% of life cycle energy		
Detached house archetypes	1	0.40	6.23	12.52
	2	0.26	4.88	12.12
	3	0.24	5.61	11.83
	4	0.34	5.96	12.98
	5	0.43	7.04	14.75
	6	0.45	6.57	14.09
Semi-detached house/end-terraced house archetypes	7	0.46	5.42	12.87
	8	0.45	5.36	13.13
	9	0.47	5.45	12.94
	10	0.46	5.43	12.91
Mid-terraced house/apartment archetypes	11	0.43	5.35	12.79
	12	0.43	4.81	10.56
	13	0.25	5.14	10.34

5.4 Cost evaluation results of the different house scenarios

This section presents the results and discussion of the life cycle cost analysis and marginal abatement cost.

5.4.1 Life Cycle Cost Analysis (LCCA) results

This sub-section presents the results and discussion of the discounted life cycle costs of retrofitting, operating and maintaining, energy and disposal for all archetypes under the BaseCase, Current Regulations and Passive House scenarios.

Discounted life cycle costs at archetype level

Tables 5.11a – 5.11c show the discounted life cycle costing by archetype for BaseCase, Current Regulations and Passive House scenarios, respectively. Results are presented based on the NPV for each life cycle phase for each house scenario. For the BaseCase scenario, LCC range from €16,847 - 62,280. Detached house archetypes show the highest range of LCC, representing €46,188 - €62,280. Semi-detached house/end-terraced house archetypes recorded the lowest range of €26,107 - €29,956. Mid-terraced house/apartment archetypes recorded a range of €16,847 - €52,199. The higher range of LCC in detached house archetypes reflects their higher operating and maintenance, energy and disposal costs, all of which are associated with higher wall, roof, floor and window areas. In addition, a major factor contributing to the higher LCC of detached houses is their use of oil compared to the other dwelling types that are running on gas. The price of gas in Ireland in 2005 was approximately 60% that of oil. On the other hand, the lower LCC of the semi-detached house/end-terraced house archetypes can be explained by their lower costs of those.

A comparison between the Current Regulations and Passive House scenarios also indicate that retrofitting from Current Regulations to Passive House scenario suggests the lower LCC, but accompanied by lower emissions compared to the Passive house scenario. Along this continuum, detached houses are still providing the lowest LCC, but cannot be achieved without first investing the LCC of the BaseCase scenario. It therefore suggests that the BaseCase scenario still provides the lowest LCC.

As the archetype dwelling type with the lowest discounted LCC will be accepted as most cost effective, one could come to the conclusion that if the decision is to maintain rather than renovate, semi-detached house/end-terraced house archetypes would be first choice, followed by mid-terraced house/apartment archetypes, especially with limited available funding.

Table 5.11a: BaseCase scenario discounted LCC (€) at archetype level across life cycle phases

Dwelling type	**Archetype reference**	**Operational energy cost**	**Operation and maintenance**	**Retrofit**	**Disassembly**	**LCC**
Detached house archetypes	1	37,735	11,597	-	172	49,504
	2	44,680	8,555	-	172	53,407
	3	54,411	7,698	-	172	62,280
	4	39,205	8,532	-	172	47,909
	5	39,128	13,513	-	172	52,813
	6	33,278	12,739	-	172	46,188
Semi-detached house/end-terraced house archetypes	7	18,182	11,603	-	172	29,956
	8	18,182	7,753	-	172	26,107
	9	18,182	8,429	-	172	26,783
	10	18,182	7,859	-	172	26,212
Mid-terraced house/apartment archetypes	11	16,608	5,955	-	172	22,734
	12	10,680	5,995	-	172	16,847
	13	46,318	5,709	-	172	52,199

As can be seen in Table 5.12b below, Current Regulations scenario resulted in significant LCC increases compared to the BaseCase scenario as LCC range from €53,902 - €107,412 due to additional costs of retrofitting to the thermal level of the Current Regulations scenario. Detached house archetypes display the highest LCC range for the Current Regulations scenario as LCC ranges from €71,308 - €107,412. Although, operation energy costs for detached houses reduced as they switched to gas compared to the BaseCase scenario, their higher LCC can still be explained as the associated energy cost savings were offset by the increased costs of retrofitting, maintenance and disposal due mainly to those reasons given at archetype LCA level. Semi-detached house/end-terraced house archetypes recorded the lowest as LCC range from €59,566 - €65,014. For the mid-terraced house/apartment archetypes, LCC range from €53,902 - €66,221.

Overall, as it can be seen above, the ranges of LCC in the Current Regulations scenario indicate that the more energy efficient the scenario, the higher its LCC. If the decision is to renovate to Current Regulations scenario, one could conclude that detached house archetypes present a good choice, especially when considered in line with the CO_2 abatement potential identified in the environmental impact results and in line with the main aim of this study. This is in contrast to the LCCA accept/reject decision discussed for the BaseCase scenario above, especially as the decision was not whether or not a given archetype dwelling type within the BaseCase scenario is cost effective, but for the application being considered.

Table 5.11b: Current Regulations scenario discounted LCC (€) at archetype level across life cycle phases

Dwelling type	Archetype reference	Operational energy cost	cost)	Retrofit	Disassembly	LCC
Detached house archetypes	1	29,939	12,335	60,074	218	102,566
	2	18,928	9,245	58,087	218	71,308
	3	16,409	8,404	55,808	218	80,839
	4	15,753	10,567	44,770	218	71,308
	5	15,753	13,928	77,513	218	107,412
	6	15,753	13,457	72,977	218	102,406
Semi-detached house/end-terraced house archetypes	7	11,249	12,155	41,392	218	65,014
	8	11,249	8,439	40,470	218	60,376
	9	11,249	9,124	40,567	218	61,158
	10	11,249	8,550	39,548	218	59,566
Mid-terraced house/apartment archetypes	11	10,660	6,574	37,342	218	54,794
	12	10,660	6,676	36,347	218	53,902
	13	14,178	6,785	45,040	218	66,221

Similarly, it can be seen in Table 5.12c below that the Passive House scenario resulted in significant LCC increases compared to the BaseCase scenario as LCC range from €81,201- €195,903 due to additional costs of retrofitting to the thermal level of the Passive House scenario. These costs are also associated with greater uptake of energy saving components compared to the Current Regulations scenario. Detached house archetypes display the highest LCC range as LCC ranges from €102,606 - €195,903 due those reasons earlier given above in support of the Current Regulations scenario. For the semi-detached house/end-terraced house archetypes, LCC range from €91,525 - €97,447. Mid-terraced house/apartment archetypes recorded the lowest as LCC range from €81,201 - €93,007 due to the lower cost of air source heat pump (ASHP) compared to ground source heat pump (GSHP) used in the other dwelling types.

Similar to the case of the Current Regulations discussed above, if the decision is to renovate to Passive House scenario, one could conclude that detached house archetypes present a good choice, especially when considered in line with the CO_2 abatement potential identified in the environmental impact results and in line with the 2020 emissions reduction targets of both the EU and Ireland.

Table 5.11c: Passive House scenario discounted LCC (€) at archetype level across life cycle phases

Dwelling type	Archetype reference	Operational energy cost	Operation and maintenance (non-energy cost)	Retrofit	Disassembly	LCC
Detached house archetypes	1	7,771	13,506	95,070	219	116,566
	2	10,307	10,354	93,871	219	102,606
	3	10,307	10,242	91,592	219	112,360
	4	10,354	12,268	79,766	219	102,606
	5	10,237	69,870	112,509	219	192,835
	6	10,237	77,473	107,973	219	195,903
Semi-detached house/end-terraced house archetypes	7	7,365	13,475	76,388	219	97,447
	8	7,365	9,646	76,485	219	93,715
	9	7,365	10,307	75,563	219	93,454
	10	7,365	9,736	74,205	219	91,525
Mid-terraced house/apartment archetypes	11	7,522	8,263	66,760	219	82,764
	12	7,522	7,695	65,765	219	81,201
	13	10,005	7,538	75,246	219	93,007

It would be recalled that all these figures as shown in the tables were calculated using those equations in Section 4.6.2 (Life cycle cost analysis) under methodology. The equations are specifically derived for the purposes of this study based on knowledge from similar examples, e.g. Life cycle costing manual for the Federal energy management programme NIST Handbook 135 US Department of Energy (1996).

Life cycle costs at archetype national stock level

This section accounts for the results of the LCC at national stock level across life cycle phases.

Table 5.12 shows estimated national LCC by archetype for each scenario. The NPVs for all life cycle phases were calculated for all archetypes under the BaseCase scenario. Estimated national housing stock LCC are obtained by summing NPVs by archetype and life cycle phase for each scenario. The results show that the archetype stock model estimates residential national stock LCC to be €32,585million for the BaseCase scenario, comprising €21,350million, €6,304.3million and €4,930.7million of detached house, semi-detached house/end-terraced house archetypes and mid-terraced house/apartment archetypes, respectively. All of the above findings are resulting from those reasons earlier discussed at archetype LCA and LCC levels above.

Table 5.12: National discounted LCC (€ million) by archetype for the different scenarios

Scenario	Detached house archetypes	Semi-detached house/end-terraced house archetypes	Mid-terraced house/apartment archetypes	Stock total
BaseCase	21,350.0	6,304.3	4,930.7	32,585.0
Current Regulations	38,696.1	14,187.9	10,863.9	63,747.9
Passive House standard	52,662.1	21,670.7	16,208.4	90,541.2

For the Current regulations scenario, national stock LCC increased from €32,585million to €63,747.9million, comprising €38,696.1million, €14,187.9million and €10,863.9million of detached house, semi-detached house/end-terraced house archetypes and mid-terraced house/apartment archetypes, respectively when compared to the BaseCase scenario.

Similar to the case at archetype LCC level above, the passive house scenario at national stock level displays greater increases, as national stock LCC increased from €32,585million to €90,541.2million, comprising €52,662.1million, €21,670.7million and €16,208.4million for detached house archetypes, semi-detached house/end-terraced house archetypes and mid-terraced house/apartment archetypes, respectively when compared to the BaseCase scenario.

A comparison between Current Regulations and Passive House scenario shows that national stock LCC increases by approximately 42% compared to the Current Regulations scenario. The corresponding share increases for detached house archetypes, semi-detached house/end-terraced house archetypes and mid-terraced house/apartment archetypes are 49%, 34.5% and 36%, respectively.

On the basis of the above discussion, one could conclude that in the event of limited funding, the current standard option provides a good choice for the national stock of housing. However, with enough funding for upgrade projects, the conclusion would be that the passive house option represents a good selection especially as the option saves more money than it costs overtime.

5.4.2 Marginal abatement cost (MAC) results

This section accounts for the results of the GHG abatement of the retrofit scenarios and the corresponding costs of a quantitative estimate of the retrofitting abatement costs of avoided GHG for the years 2020 and 2055. While the abatement opportunities presented here for the year 2020 represent those within the reductions expected for the portion of the residential sector of the EU and Ireland 20% emissions reduction targets for same period, those of the year 2055 are expected to cover the reductions anticipated in the 2050, the next stage of European Energy Policy (EC, 2011).

Abatement case for 2020 and 2055

Figures 5.9, 5.10 and 5.11 give estimated GHG abatement and the retrofitting abatement costs of avoided GHG 2020 and 2055 by archetype dwelling type for the Current Regulations and Passive House scenarios. The GHG abatement was calculated as the difference between the emissions of the BaseCase scenario and those of the Current Regulations and Passive House scenarios, and between the Current Regulations and Passive House scenarios. The savings per tCO_2-eq of avoided GHG in 2020 and 2055 were calculated using Equation 4.20.

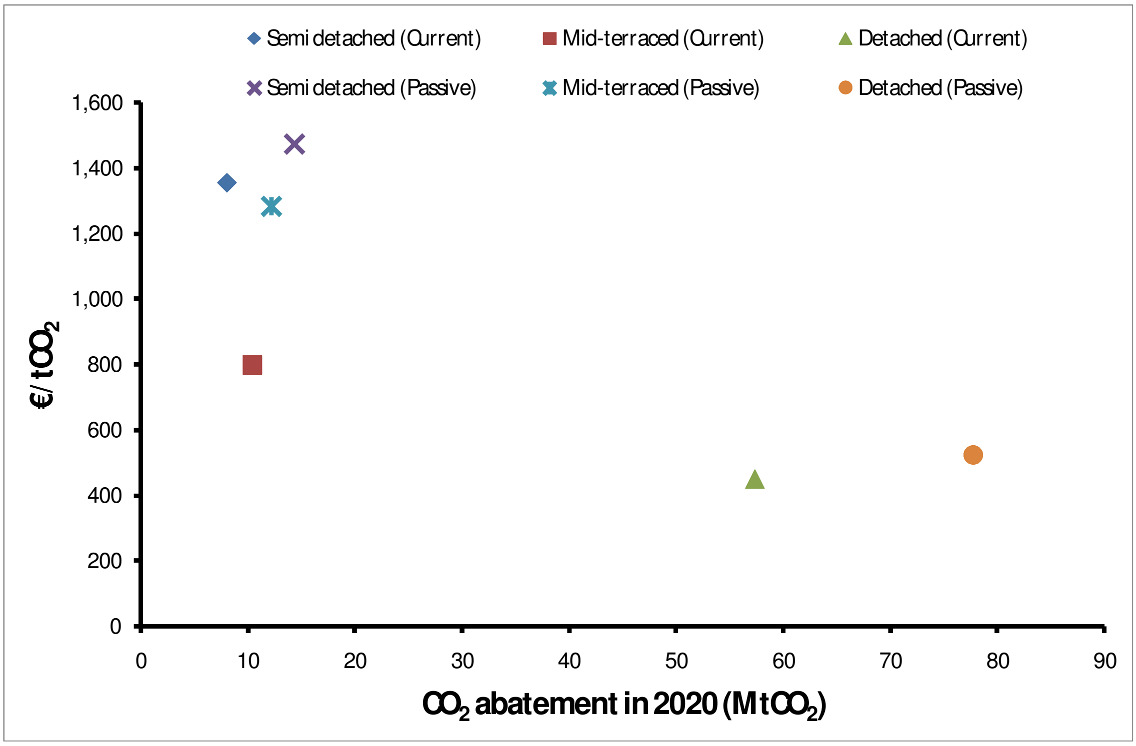

Figure 5.9: Current Regulations and Passive House scenarios abatement potential in year 2020

Overall, the retrofitting abatement costs for the Current regulations, Passive House scenario, and Current regulations versus Passive House scenario are high compared to the current EU market price of Allowances, due mainly to low emissions savings. However, for the Current regulations scenario, results show that the quantity of GHG abatement were estimated to be 76MtCO_2-eq and 211MtCO_2-eq at the corresponding retrofitting abatement costs of avoided GHG of €592/tCO_2-eq and €148/tCO_2-eq in 2020 and 2055, respectively. Detached house archetypes display the highest GHG abatement of 57.4MtCO_2-eq at the lowest retrofitting abatement cost of €447/tCO_2-eq and 159.5MtCO_2-eq at a retrofitting abatement cost €109/tCO_2-eq in 2020 and 2055, respectively. Semi-detached house/end-terraced house archetypes provide the lowest abatement of 8MtCO_2-eq at the lowest retrofitting abatement cost of €1,357/tCO_2-eq and 22.5MtCO_2-eq at a retrofitting abatement cost €352/tCO_2-eq in 2020 and 2055, respectively. Mid-terraced house/apartment archetypes show abatement potential of 10.4MtCO_2-eq at a retrofitting abatement cost of €798/tCO_2-eq and 29MtCO_2-eq at a retrofitting abatement cost €204/tCO_2-eq in 2020 and 2055, respectively.

In contrast to the case in the year 2020, the retrofitting abatement costs for both the Current regulations and Passive House scenarios are low compared to the case in the year 2055, due mainly to higher emissions savings (See Figure 5.10). However, Passive House scenario provided a greater abatement potential but at higher retrofitting abatement costs, representing 104.2MtCO_2-eq at €741/tCO_2-eq and 289.6MtCO_2-eq at €200/tCO_2-eq in 2020 and 2055, respectively. Similar to the case of the Current Regulations scenario, detached house archetypes display the highest GHG abatement of 77.8MtCO_2-eq at the lowest retrofitting abatement cost of €522/tCO_2-eq and 216MtCO_2-eq at a retrofitting abatement cost €145/tCO_2-eq in 2020 and 2055, respectively. Semi-detached house/end-terraced house archetypes provide an abatement potential of 14.4MtCO_2-eq at the highest retrofitting abatement cost of €1,473/tCO_2-eq and 40MtCO_2-eq at the highest retrofitting abatement cost €386/tCO_2-eq in 2020 and 2055, respectively. Mid-terraced house/apartment archetypes show the lowest abatement potential of 12.2MtCO$_2$-eq at a retrofitting abatement cost of €1,283/tCO$_2$-eq and 33.5MtCO$_2$-eq at a retrofitting abatement cost €335/tCO$_2$-eq in 2020 and 2055, respectively.

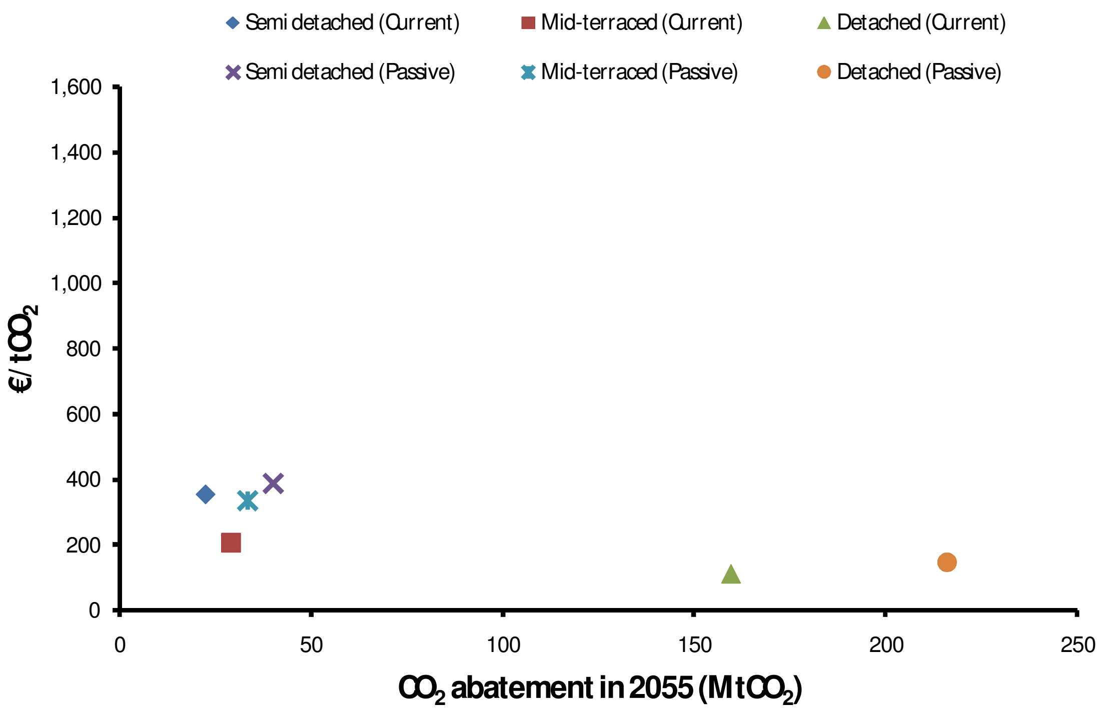

Figure 5.10: Current Regulations and Passive House scenarios abatement potential in year 2055

For the Current regulations vs. Passive House scenario, results show that the quantity of GHG abatement were estimated to be 21.2MtCO$_2$-eq and 78.7MtCO$_2$-eq at the corresponding retrofitting abatement costs of avoided GHG of €1,141/tCO$_2$-eq and €341/tCO$_2$-eq in 2020 and 2055, respectively (See Figure 5.10). Detached house archetypes display the highest GHG abatement of 15.3MtCO$_2$-eq at the lowest retrofitting abatement cost of €731/tCO$_2$-eq and 56.5MtCO$_2$-eq at a retrofitting abatement cost €247/tCO$_2$-eq in 2020 and 2055, respectively. Semi-detached house/end-terraced house archetypes show abatement potential of of 4.7MtCO$_2$-eq at the lowest retrofitting abatement cost of €1,622/tCO_2-eq and 17.4MtCO_2-eq at a retrofitting abatement cost €429/tCO_2-eq in 2020 and 2055, respectively. Mid-terraced house/apartment archetypes provide the lowest abatement of 1.2MtCO_2-eq at a retrofitting abatement cost of €4,366/tCO_2-eq and 4.6MtCO_2-eq at a retrofitting abatement cost €1,165/tCO_2-eq in 2020 and 2055, respectively.

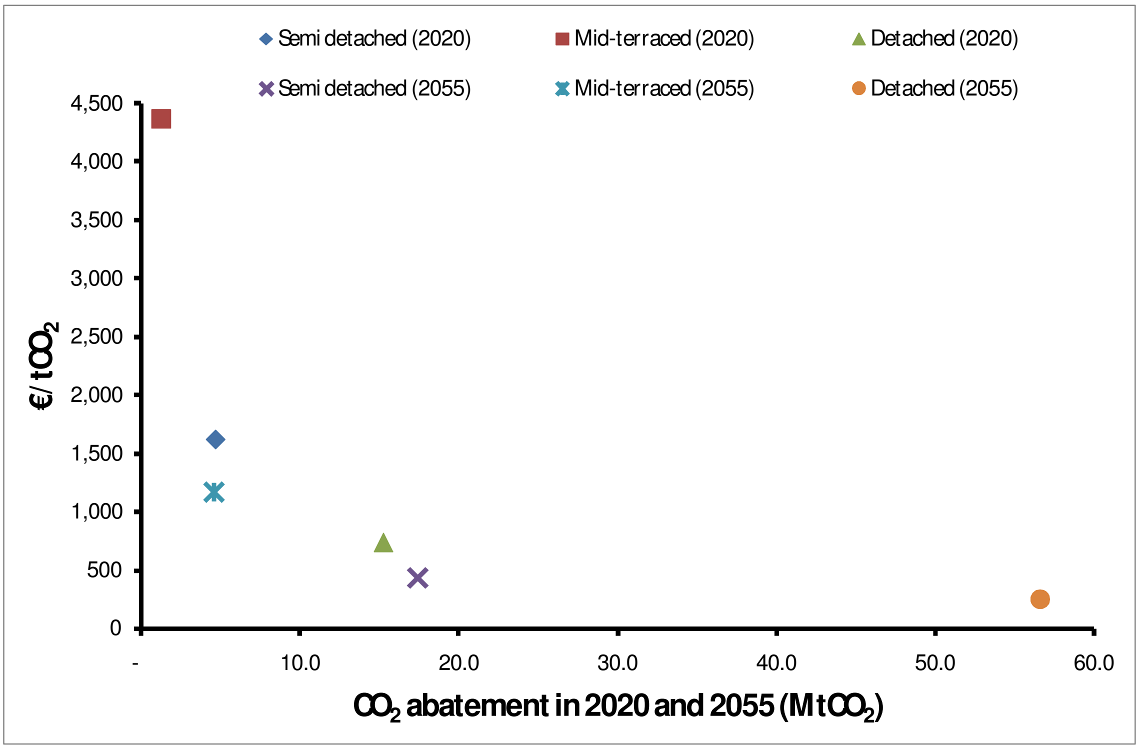

Figure 5.11: Current Regulations versus Passive House scenarios abatement potential in years 2020 and 2055

Around 4% of the abatement opportunities identified in this study represent embodied emissions of production of materials and technical components. Data on this aspect would be useful in the event that the European Union Emissions Trading scheme (EU-ETS) is extended to the residential sector. The EU-ETS is the Emissions Trading Scheme of the EU specifically established as the first international trading system for

CO_2 emissions reductions in the world whilst the scheme is mandatory for large emitters.

It should be noted that the retrofitting abatement costs identified in this study are positive, suggesting that the potential energy efficiency improvements will require adequate investments. This raises concerns about the need to remove barriers to investment, as a positive retrofitting abatement cost indicates the amount per tonne CO_2 emissions that the investor is expected to invest in the upgrade projects. With positive retrofitting costs to society, both tenants and homeowners may be unwilling to invest in upgrade projects. This is particularly so as tenants may consider the payback time on energy efficiency improvements too long, and in particular as they desire the benefits of their energy efficiency investments before moving house. Similarly, landlords may be unwilling to invest in energy efficiency upgrades where the financial benefits accrue to their tenants, especially as payback time may also be considered too long.

Overall, the abatement potential in this study is expected to contribute significantly to the residential portion of Ireland's and EU reduction targets of 20% emissions reductions by 2020 compared to 2005 levels. The abatement opportunities therefore underscores the need for rigorous enforcement of the current building codes, as well as reviews the existing regulations to meet passive house standard measures. Such enforcement should be timely and at regional and local levels.

5.5 Conclusions to Chapter 5

The key conclusions from this chapter are:

- Reducing operational energy becomes intractable due to the poor quality of many of the representative archetype houses. This is most common with detached houses.

Moreover, the level of reductions depends on the Irish electricity generation and household fuel mixes. For example, all buildings under the Current Regulations scenario still depend on use of fossil fuels for heating even after retrofitting. Similarly, the Irish electricity generation mix is still largely based on fossil fuels. Due to this, emissions from operational phase have remained dominant for all scenarios when compared to the other life cycle phases.

- For the BaseCase scenario, operational energy/emission remains dominant for all archetypes when compared with other life cycle phases. Overall, detached houses display higher operational energy use, mainly a result of the higher floor and window areas including the use of oil-fired boilers. Maintenance and disassembly phases are of minor significance.
- The weighted average dwelling is responsible for 45, 478kWh/yr operational energy consumption, which is found to be consistent with national statistics, especially when all relevant upstream processes in the supply and production of fuels that occurred in Ireland and abroad are considered.
- The weighted average dwelling energy consumption can be reduced by 51% and 75% in the Current Regulations and Passive House standard scenarios, respectively compared to the BaseCase scenario. Another comparison between the Current Regulations and Passive House standard scenarios indicates that the weighted average dwelling operational energy consumption can be reduced by 47.6% relative to the Current Regulations scenario.
- The proportion of international sources of operational energy consumption by the weighted average dwelling represents 5,930kWh/yr (13%) of the life cycle's total in the BaseCase scenario. However, this can be reduced by 61.7% and 72.4% in the

Current Regulations and Passive House standard scenarios, respectively. Similarly, retrofitting from the Current Regulations scenario to Passive House standard scenario will result in 27.8% savings in energy attributable to imported fossil fuels.

- The result shows that the archetype stock model estimates residential sector total national operational primary energy-related emissions to be 9, 447ktCO_2-eq. in 2005. This figure is found to be consistent with national statistics, especially when all relevant upstream processes in the supply and production of fuels that occurred in Ireland and abroad are considered. For the BaseCase scenario, detached houses display the highest national operational emissions (68.7%), followed by semi-detached house/end-terraced house archetypes (16%) and mid-terraced house/apartment archetypes (15.3%), respectively. For the Current Regulations scenario, detached houses have the highest operational national emissions savings relative to BaseCase, representing (54%), followed by mid-terraced house/apartments (47%) and semi-detached house/end-terraced house archetypes (38%), respectively. For the Passive House standard scenario, detached houses have the highest operational national emissions savings relative to BaseCase, representing (76%), followed by mid-terraced house/apartment archetypes (69%) and semi-detached house/end-terraced house archetypes (66%), respectively. A further comparison between the Current Regulations and Passive House standard scenarios indicates that national emissions savings of 46% could be achieved in the Passive House standard scenario relative to the the Current Regulations scenario. Along this continuum, detached houses have the highest operational national emissions savings in the Passive House standard scenario relative to the Current Regulations scenario, representing (47.4%). This is followed by mid-terraced house/apartment (41.5%) and semi-detached house/end-terraced house (45.5%), respectively.

- Life cycle energy reduces for most archetypes by 41% and 65% in the Current Regulations and the Passive House standard scenarios, respectively. A comparison between the Current Regulations and the Passive House standard scenarios indicates for most dwellings life cycle energy savings represent at least 39% of life cycle total relative to the Current Regulations scenario. Detached houses display the highest life cycle energy savings potential, due to their higher energy consumption compared to the other dwelling types. This is followed by semi-detached house/end-terraced house archetypes and Mid-terraced house/apartment archetypes, respectively. A comparison between the Current Regulations and the Passive House standard scenarios indicates for most dwellings at least 43.4% weighted mean life cycle energy savings relative to the Current Regulations scenario.
- The results show that the archetype stock model estimates national life cycle emissions for the BaseCase, Current Regulations and Passive House standard scenarios to be 9,838ktCO_2-eq., 5,618ktCO_2-eq and 4,045ktCO_2-eq, respectively.
- Retrofitting the BaseCase house to the thermal level of the Current Regulations and Passive House scenarios resulted in 43% and 59% national life cycle emissions savings, respectively. A further view at retrofitting from Current Regulations scenario to Passive House scenario suggests national emissions savings of 28%. Detached houses under the BaseCase scenario displays the highest life cycle national emissions (68%) followed by semi-detached house/end-terraced house archetypes (16.5%) and mid-terraced house/apartment archetypes (15.5%), respectively. In the Current Regulations scenario, detached houses have the highest emissions reduction potential relative to BaseCase, representing approximately (48%), followed by mid-terraced house/apartment archetypes (39.5%) and semi-detached house/end-terraced house archetypes (27.7%), respectively. Similarly, in

the Passive House standard scenario, detached houses have the highest emissions reduction potential relative to BaseCase, representing approximately (64.5%), followed by semi-detached house/end-terraced house archetypes (49%) and mid-terraced house/apartment archetypes (45.4%), respectively. A further comparison between the Current Regulations and Passive House standard scenarios indicates that national life cycle emissions savings of 28% could be achieved in the Passive House standard scenario relative to the the Current Regulations scenario. Along this continuum, detached houses have the highest life cycle national emissions savings in the Passive House standard scenario relative to the Current Regulations scenario, representing (32.3%). This is followed by semi-detached house/end-terraced houses archetypes (29.7%) and mid-terraced house/apartment archetypes (9.7%), respectively.

- The cumulative embodied energy for most archetypes for all scenarios is at least 0.24%, 4.8% and 10.3% in the Current Regulations and Passive House standard scenarios, respectively. Detached houses have the highest range of cumulative embodied energy, followed by semi-detached house/end-terraced house archetypes and mid-terraced house/apartment archetypes, respectively.

- The BaseCase scenario has the lowest range of life cycle costs (LCC) for all archetypes as they were not retrofitted. This is followed by: Current Regulations scenario; retrofitting from the Current Regulations scenario to the Passive House scenario; and Passive House scenarios, respectively. Detached houses show the highest range of LCC for all archetypes for the BaseCase scenario, mainly a result of the use of oil compared to the other dwelling types that are running on gas. Overall, detached houses show the highest range of LCC for the retrofitted scenarios. This is followed by semi-detached house/end-terraced house archetypes and mid-terraced house/apartment archetypes, respectively. As the archetype dwelling type with the lowest discounted LCC will be accepted as most cost effective, one could come to the conclusion that if the decision is to maintain rather than renovate, semi-detached house/end-terraced house archetypes would be first choice, followed by mid-terraced house/apartment archetypes, especially with limited available funding.

- As the model indicates that the more energy efficient the scenario, the higher its LCC. If the decision is to renovate, one could conclude that detached house archetypes present a good choice in the Current Regulations scenario if there is limited funding. However, with adequate funding, it is suggested that renovation of detached houses should be carried out based on: Passive House scenario; and retrofitting from Current Regulations scenario to the Passive House scenario, in that hierarchical order of importance, especially when considered in line with the CO_2 abatement potential identified in the environmental impact results and in line with the main aim of this study.

- The abatement opportunity in 2055 is greater in terms of costs and emissions savings than for the year 2020 for all retrofitted scenarios. The 2020 retrofitting costs to society is mainly due to low emissions savings as most investments put into energy efficiency improvement projects in year 2020 are also meant for the year 2055.

- Detached houses provide the least retrofit costs as well as the highest emissions savings for both years 2020 and 2055 for all retrofitted scenarios.

- Finally, this chapter has shown that a total of 76MtCO_2-eq, 104.2MtCO_2-eq and 21.2MtCO_2-eq reductions could be met at retrofitting abatement costs of €592/tCO_2-eq, €741/tCO_2-eq and €1,141/tCO_2-eq by 2020 in the Current Regulations, Passive House Regulations, and Current Regulations vs. Passive House Regulations comparison, respectively. Similarly, emissions reductions for 2055 are estimated to be 211MtCO_2-eq, 289.6MtCO_2-eq and 78.7MtCO_2-eq at retrofitting costs of €148/tCO_2-eq, €200/tCO_2-eq and €341/tCO_2-eq by 2055 in the Current Regulations, Passive House Regulations, and Current Regulations vs. Passive House Regulations comparison, respectively.

- The high energy demand across the whole housing is influenced by the poor standard of many existing homes. A strategy of retrofitting is required in order to achieve the residential portion of the year 2020 emission reduction target of the government.

- Similarly, in order to achieve the abatement potential identified in the study, a clear strategy is needed to remove barriers to investment in energy efficiency projects, especially as the retrofitting costs are mainly positive.

Chapter 6: Implications for Ireland's Residential Sector Energy and Emissions Policies

6.1 Overview

In Chapter 5, the results of the various analyses were presented, discussed and interpreted. In this chapter, recommendations based on the interpretation of the results are given. These recommendations are directed towards experts in environmental and economic policy and other stakeholders.

Overall, the abatement potential in this study is expected to contribute significantly to the residential portion of Ireland's and EU reduction targets of 20% emissions reductions by 2020 compared to 2005 levels. The abatement opportunities therefore underscores the need for rigorous enforcement of the current building codes, as well as reviews the existing regulations to meet passive house standard measures. Such enforcement should be timely and at local, county and national levels.

The retrofitting abatement costs identified in this study are positive, suggesting that the potential energy efficiency improvements will require adequate investments. This raises concerns about the need to remove barriers to investment, as a positive retrofitting abatement cost indicates the amount per tonne CO_2 emissions that the investor is expected to invest in the upgrade projects. With positive retrofitting costs to society, both tenants and homeowners may be unwilling to invest in upgrade projects. This is particularly so as tenants may consider the payback time on energy efficiency improvements too long, and in particular as they desire the benefits of their energy efficiency investments before moving house. Similarly, landlords may be unwilling to invest in energy efficiency upgrades where the financial benefits accrue to their tenants, especially as payback time may also be considered too long.

As the EU and Ireland are determined to ensure that energy and emissions of consumption and production in the residential sector do not exceed a sustainable level, it is essential to formulate sustainable policies capable of being used to achieve significant emissions reductions in the residential sector. In this way emissions reductions can be translated into sustainable use of non-renewable resources, mitigation of climate change, achieving energy security, guaranteeing economic competitiveness (including justifiable use of tax payer's contribution to the national treasury) and ensuring reduced dependence on imported fossil fuels. To achieve the abatement opportunities identified in the study, all policies focus on operational phase energy and emissions including costs since the existing measures in Ireland focus on operational phase.

6.2 Recommendations

In general, a significant proportion of the investments required to retrofit the dwellings and achieve emissions savings for the year 2055 are expected to be first expended to achieve those savings for the year 2020. The balance of the investments is expected to be expended overtime as the age of the dwelling increases. Therefore, in this section, a list of recommendations considered adequate for achieving the emission savings identified for years 2020 and 2055 combined, are discussed. Using the interpretations of the results of this study, a number of recommended measures considered adequate to address residential sector energy efficiency are presented below:

6.2.1 Retrofitting national housing stock

Table 6.1 show the summary of the abatement opportunities identified in the study in the years 2020 and 2055 for all retrofitted scenarios. In this section, recommendations are given for the Current Regulations, Passive House scenarios and the Current Regulation scenario vs. Passive House scenario.

Table 6.1: Summary of abatement opportunities in years 2020 and 2055 for all retrofitted scenarios

	Scenario								
	Current Regulations			Passive House			Current Regulations vs. Passive House		
	Emission savings ($MtCO_2$-eq)	Abatement cost (€/tCO_2-eq)	Recommendation	Emission savings ($MtCO_2$-eq)	Abatement cost (€/tCO_2-eq)	Recommendation	Emission savings ($MtCO_2$-eq)	Abatement cost (€/tCO_2-eq)	Recommendation
National total (year 2020)	76	592	Provides an alternative for upgrades if funding is limited.	104.2	741	Good choice for upgrades if there is adequate funding.	21.2	1,141	Not recommended for upgrades
National total (year 2055)	211	148		289.6	200		78.7	341	
*Detached (2020)	57.4	447	Provides an alternative if there is limited funding	77.8	552	Recommended as priority dwelling type upgrade option if there is adequate funding.	15.3	731	Not recommended for upgrades
*Detached (2055)	159.5	109		216	145		56.5	247	
**Semi-detached (2020)	8	1,357	Recommended for private sector-based investments	14.4	1,473	Recommended for private sector-based investments	4.7	1,622	Not recommended for upgrades
**Semi-detached (2055)	22.5	352		40	386		17.4	429	
***Mid-terraced (2020)	10.4	798	Recommended for private sector-based investments	12.2	1,283	Recommended for private sector-based investments	1.2	4,366	Not recommended for upgrades
***Mid-terraced (2055)	29	204		33.5	335		4.6	1,165	

*Detached House archetypes, **Semi-detached house/end-terraced house archetypes, ***Mid-terraced house/apartment archetypes

1. *Recommendation: Retrofitting the housing stock to Passive House scenario*

In the event of adequate funding, a strategy of refurbishing the national housing stock to the thermal level of the Passive House scenario should be considered, especially as as the option saves more money than it costs overtime. In addition, the abatement presented in this choice is more important to meet the residential portion of the 2020 emissions reduction targets of both the EU and Ireland. However, due to the cost differential, investors are likely to shy away from energy efficiency upgrades. It therefore means a combination of measures will be required to achieve the emission reductions identified in the option.

The existing building regulations should be reviewed and enforced to incorporate passive house measures. Similarly, the Building Energy Rating (BER) providing twofold function of regulation and information on the energy performance of a dwelling at the point of sale or rental should be reinvigorated through increased inspection and monitoring. In addition, all existing financial incentives should be remodeled to be more sustainable and designed to meet the needs of only households in financial difficulty. For example, the Home Energy Savings Scheme providing a form of cash grant which is paid directly through electronic funds transfer to the applicant has the potential to increase the rate of improvement through refurbishment. However, the programme should be remodelled to include financial incentives in the provision of envelope insulation upgrades (taken cognizance of the super insulation requirement of the passive house standards), PV system, heat pumps and other micro generation devices. It should be noted that the scheme is at the moment limited to the provision of solar heating. The Warmer Homes Scheme providing assistance and grants to low-income groups for attic insulation, draught proofing, lagging jackets, energy efficient lighting, cavity wall insulation should be remodelled to take cognizance of the expected increases in the levels of insulation for the Passive House option. The Housing Aid for Older People Scheme, which is designed to pave the way for future building regulations in respect of the use of renewable energy in new house-building, should be remodelled to include existing dwellings.

Thus, a combination of the reviewed and enforced regulations and incentives could assist convert information on the quality of dwellings into long-term energy efficiency upgrades, based on a standard practice of achieving all cost-effective energy efficiency (i.e. based on a market transformation technique). The implementation of the European Energy Performance of Building Directive (EPBD) in Ireland as evident in the transposition into Irish law new building codes has made available the basis for the carrying out of a standard practice of achieving all cost-effective energy efficiency.

However, given the current economic climate in most advanced economies including Ireland, an alternative to the provision of financial incentives is to seek the intervention of the private sector. The establishment of a low interest rate loans Bank should be considered as ‘stand-by’ to assist willing households, investors and other stakeholders in the implementation of energy efficiency improvements.

2. *Recommendation: Retrofitting the housing stock to Current Regulations scenario*

However, in the event of inadequate funding, a strategy of refurbishing the national housing stock to the thermal level of the Current Regulations scenario should then be considered. Although the scenario provides a lower emissions savings, it however represents a more economically viable option compared to the corresponding Passive house scenario (See Table 6.1). In order to achieve the identified emission savings, compliance with existing building regulations requires to be much better enforced. Just like the case of the Passive House scenario, the Building Energy Rating (BER) should be reinvigorated through increased inspection and monitoring. The existing financial incentives should be amended to meet the needs of households within the Current Regulations scenario. The Warmer Homes Scheme should be adjusted to extend incentives for envelope insulation to the Current Standard scenario. Similar to case of the Passive House scenario, regulation and financial supports may well assist to long-term energy efficiency upgrades of the housing stock, using a market transformation approach.

3. *Recommendation: Retrofitting the housing stock to Current Regulations vs. Passive House scenario*

Refurbishing the national housing stock to the thermal level of the Current Regulations vs. Passive house scenario provides a much lower emission savings as well as higher retrofitting costs compared to the other scenarios. The option is therefore not economically viable, and the emissions savings will have a minor significance on the 2020 reduction target of the government. As non of the dwellings of the housing stock is presently complying with the 2010 building regulations, it is recommended that energy efficiency improvements should be carried out as recommended in the Current Regulations and Passive House scenarios relative to BaseCase scenario.

6.2.2 Retrofitting according to dwelling type

In this sub-section, recommendations are made for each of the archetype dwelling types considered in the study, using the interpretation of the results in Chapter 5.

4. *Recommendation: Retrofitting detached houses in the Passive House scenario*

Detached houses under the BaseCase scenario display the highest national operational emissions, representing approximately 6,490ktCO_2-eq (68.7%) in 2005 (See Chapter 5 under 'Conclusions') compared to the other dwelling type. If a significant proportion of this share could be reduced from the national housing stock's total, this would have significant effects on the objectives of the government of Ireland as contained in its white papers: Delivering a sustainable energy future for Ireland: The energy policy framework 2007-2020; and Maximising Ireland's Energy Efficiency – The National Energy Efficiency Action Plan (NEEAP) 2009 – 2020 (2009). Moreover the option provides the highest emissions savings at the least retrofitting costs when compared with the other dwelling types (See Table 6.1). It therefore suggests that in the event of adequate funding and the government decides to optimise the benefits of the emission savings, detached houses provide a good choice. This choice provides higher emissions savings, but at lower retrofitting costs (except for the detached houses in the Current Regulations scenario) compared to the other archetype dwelling types for all retrofitted scenarios. It would be recalled that the option saves more money than it costs overtime. Moreover, it provides the much needed emissions savings for 2020 emission reduction targets of both the EU and Ireland.

To achieve the identified emission savings for detached houses in the Passive House scenario would require a combination of regulation, financial incentives and information. As discussed in the previous sections, the existing building regulations should be updated and enforced to incorporate passive house standards. Just as discussed in the previous sections, the BER playing the dual role of regulation and information should be reinvigorated for much better enforcement. As reducing operational energy becomes intractable due to the poor quality of many of the representative archetype houses (most common with detached houses), priority should be given to envelope insulation, followed by heating system improvements.

5. *Recommendation: Retrofitting detached houses in the Current Regulations scenario*

Detached houses under the Current Regulations scenario provide the greatest emission savings and at the least retrofitting costs compared to the other dwelling types. It therefore suggests that in the event of limited funding and the government decides to prioritise improvement projects, detached houses provide a good choice. Similar to the case of the Passive House scenario, to achieve the identified emission savings for detached houses in the Current Regulations scenario would require a combination of regulation, financial incentives and information, the existing building regulations should be much better enforced. All other recommendations given in support of the detached houses in the Passive House scenario should also be applied in the case of the Current Regulations scenario.

6. *Recommendation: Retrofitting detached houses in the Current Regulations vs. Passive House scenario*

Detached houses under the Current Regulations vs. Passive House scenario provides the greatest emission savings compared to the other dwelling type, and at a much lower retrofitting cost. This option is not economically viable compared to detached houses in the other retrofitted scenarios for both years 2020 and 2055. However, in prioritising improvement projects, detached houses as recommended under the other two scenarios should be considered. This option is therefore recommended for private investments, such as the low interest rate loans bank earlier discussed. It would be recalled that the option saves more money than it costs overtime.

7. *Recommendation: Retrofitting semi-detached house/end-terraced house archetypes in the Current Regulations scenario*

Semi-detached house/end-terraced house archetypes under the Current Regulations scenario provides the lowest emission savings compared to the other dwelling types, and at much higher retrofitting cost (approximately three times that of detached houses and almost twice that of mid-terraced house/apartment archetypes). Moreover, the emission savings are not likely to make significant effects on the 2020 emission reduction target of the government. The option is therefore not recommended for the limited tax payers' funds. This option is recommended for energy efficiency improvements based on a combination of regulation, information (e.g. BER as earlier discussed) and private sector investments from the low interest rate loans bank.

8. *Recommendation: Retrofitting semi-detached house/end-terraced house archetypes in the Passive House scenario*

Semi-detached house/end-terraced house archetypes under the Passive House scenario provide emission savings of approximately 18% and 14% that of detached houses for the years 2020 and 2055, respectively, and at much higher retrofitting costs (See Table 6.1). Moreover, the option is not economically viable, and the emission savings are not likely to make significant effects on the 2020 emission reduction targets of the government. The option is therefore not recommended for the limited tax payers' funds. Just like the case of the Current scenario, this option is recommended for energy efficiency improvements based on a combination of regulation, information (e.g. BER as earlier discussed) and private sector investments from the low interest rate loans bank.

9. *Recommendation: Retrofitting semi-detached house/end-terraced house in the Current Regulations vs. Passive House scenario*

Semi-detached house/end-terraced house archetypes under the Current Regulations vs. Passive House scenario equally represent low emission savings, and at highest retrofitting costs compared to the other dwelling types. Similar to the case of the Passive House scenario, the option is not economically viable, and the emission savings are not likely to make significant effects on the 2020 emission reduction targets of the government. The option is therefore not recommended for proritised energy efficiency improvement by the government.

10. Recommendation: Retrofitting mid-terraced house/apartment archetypes in the Current Regulations scenario

Mid-terraced house/apartment archetypes under the Current Regulations scenario equally represent low emission savings, and at a relatively high retrofitting cost compared to the other dwelling type. The emission savings are not likely to make significant effects on the 2020 emission reduction targets of the government. The option is therefore not recommended for proritised energy efficiency improvement of the government. A combination of regulation, information and private sector investments from the low interest rate loans bank should be applied to carry out the refurbishment of the option.

11. Recommendation: Retrofitting mid-terraced house/apartment archetypes in the Passive House scenario

Mid-terraced house/apartment archetypes under the Passive House scenario equally represent low emission savings, and at second highest retrofitting costs compared to the other dwelling types. The emission savings are not likely to make significant effects on the 2020 emission reduction targets of the government. The option is therefore not recommended for proritised energy efficiency improvements of the government. A combination of regulation, information and private sector investments from the low interest rate loans bank should be applied to carry out the refurbishment of the option.

12. Recommendation: Retrofitting mid-terraced house/apartment archetypes in the Current Regulations vs. Passive House scenario

Mid-terraced house/apartment archetypes under the Current Regulations vs. Passive House scenario provide the lowest emission savings, and at the highest retrofitting costs when compared overall in the results. The emission savings will not make significant effects on the 2020 emission reduction targets of the government. It would be recalled that all dwellings within the housing stock are currently below compliance with the current building regulations. The option is therefore not recommended for energy efficiency improvements. A combination of regulation, information and private sector investments from the low interest rate loans bank applied to any of the other two retrofit scenarios as previously discussed is preferred.

6.2.3 Conclusions to Chapter 6

The key conclusions from this chapter are:

- In the event of adequate funding, a strategy of refurbishing the national housing stock to the thermal level of the Passive House scenario should be considered, especially as the option saves more money than it costs overtime.
- However, in the event of inadequate funding, a strategy of refurbishing the national housing stock to the thermal level of the Current Regulations scenario provides an alternative.
- Within the Passive House scenario, a combination of the reviewed and enforced 2010 building regulations to include passive house measures and incentives could assist convert information on the quality of dwellings into long-term energy efficiency upgrades, based on a standard practice of achieving all cost-effective energy efficiency.
- For the Current Regulations scenario, a combination of the enforcement of the 2010 building regulations and incentives could assist convert information on the quality of dwellings into long-term energy efficiency upgrades, based on a standard practice of achieving all cost-effective energy efficiency.

- Within limited funding, priority should be given to detached houses in both the Current and Passive House scenarios in prioritising energy efficiency improvements.
- Emission savings from both Semi-detached house/end-terraced house archetypes and mid-terraced house/apartment archetypes are too low to make any significant effects on the emission reduction targets of both the EU and Ireland for the year 2020. These options are not recommended as priority energy efficiency improvement projects, but their refurbishment should be considered based on a combination of regulation, information and private sector-based financial support.
- Refurbishing from Current Regulations to Passive House scenario in all cases will not have any significant effects on the emission savings required for the years 2020 2055, and is equally not economically viable.
- Overall, refurbishment should be based on the Current Regulations and Passive House scenarios relative to BaseCase rather than from the Current Regulations to Passive House scenario.

Chapter 7: Conclusions and Further Research

7.1 Conclusions

In this Chapter, the conclusions of the individual chapters are combined and summarised to reach the conclusions of the thesis. The overall conclusions of the thesis are discussed below.

The aim of this study is to determine to what extent energy, emissions and life cycle costs can be reduced by retrofitting the housing stock, and to use these findings to make policy recommendations to mitigate environmental impacts in the residential sector.

This aim has been realized within the hybrid LCA that was performed. The first part of this work under Section 4.2 describes the development of a methodology for characterising residential dwelling stocks into archetypes and its implementation using Irish data. The archetype development concept as presented in this study was shown to be an adaptable tool for assessing the life cycle impacts of the existing Irish housing stock for the different house scenarios. A major benefit of the general technique is its ability to provide an initial synopsis of the characteristics of the individual distinct archetypes. This provides typical homeowners a quick overview of the characteristics of a building similar to their own. Furthermore, homeowners or consultants can use the archetype technique for analysis prior to energy efficiency upgrades. Overall, the archetype model is directed towards experts from environmental policy for depicting the characteristics of the different classes of house in the residential sector.

This study was carried out as a case study to display the utilisation of archetype model to assess the energy and GHG emissions of the existing Irish housing stock across life cycle phases. This was first time in Ireland that the archetype model will be used to characterise the entire housing stock, using statistical analysis, knowledge of construction details and cluster analysis. The Irish housing stock can be characterised by 13 representative archetypes, obtained by classifying the housing stock into 9 classes of construction detail and 9 household key variables of energy use. The archetype methodology can be applied in other countries using the respective housing databases. The existing housing database could be improved (e.g. by SEAI) through the regular collection and updating of energy use data in a sample of Irish dwellings, thereby helping to minimise the sources of uncertainty and the need to manage deficiencies in the housing database. The possibility of reducing sources of uncertainty in the housing database is worth including in other archetype development studies.

The second part of this study involves stock modelling activities using the developed representative archetypes. As stock modelling methods in current use in Ireland are based mainly on end use energy and do not allow a whole house life cycle assessment of primary energy and primary energy-related emissions, a stock modelling exercise based on hybrid LCA methodology was carried out by: assessing the life cycle impacts of regular maintenance with costs of operation, maintenance and repair (OM&R), and disassembly of the developed archetypes under the BaseCase scenario; identifying two relevant retrofitting scenarios – 'meet current building regulations' (Current Regulations standard) and 'meet anticipated future regulations' (Passive House standard); and assessing the life cycle impacts of retrofitting, maintenance, operation, and disassembly including their costs for all archetypes under these retrofit scenarios. The hybrid LCA involves a combination of methods and databases that allow a holistic view of the emissions induced by retrofitting the housing stock across life cycle phases and along domestic and international sources.

For the first time in Ireland, the use of a hybrid approach was demonstrated to evaluate the share of the international arising primary energy and emissions for operating the building and embodied energy including those for services (i.e. installation of energy savings components and maintenance of appliances). A weighted average archetype operational primary energy from international sources was found to be 13% of the total operational primary energy for the BaseCase scenario. The weighted average archetype operational primary energy from international sources reduced from 13% to 10% in the Current Regulations scenario as the building switches from the use of oil to gas which has a lower energy for fuel supply chain processes that occurred abroad than oil. In contrast to the case in the Current Regulations scenario, the weighted average archetype operational primary energy from international sources increased from 13% to 14% in the Passive House scenario as the building now runs only on grid electricity, and in particular as the Irish electricity grid mix is still largely based on imported fossil fuels.

Given this result, it can be seen that imports can play a major role in the analysis of the complete view of the energy and emissions attributable to the Irish residential sector as well as providing additional information for policy makers. It should be noted that imported materials were taken into consideration in the analysis. This explains why the weighted average life cycle energy increased from 13% to 14% when retrofitted from the Basecase scenario to the Current Regulations scenario. This suggests the need for a more integrated EU policy towards imports.

For the BaseCase scenario, the weighted average archetype cumulative embodied energy was estimated to be approximately 0.4% of the life cycle total energy. The weighted average archetype cumulative embodied energy increased from 0.4% to 5.7%

and 12.6% of the life cycle's total for the Current Regulations and Passive House scenarios, respectively. This result suggests the importance of embodied energy in retrofitting the existing Irish housing stock, and in particular as it provides an opportunity for further reducing the proportions of embodied energy as the building becomes more energy efficient.

Similarly, the weighted average archetype embodied energy due to services was found to be 29% of the cumulative embodied energy for the BaseCase scenario. This proportion reduced to 8.9% and 7.9% for the Current Regulations and Passive House scenarios, respectively. This reflects the progressive reductions in the level of services, as the building becomes increasingly energy efficient. This result suggests the importance of the energy required for services in a retrofit project.

The work led to the following main conclusions:

The study looks at the pre1960 – 2002 portion of the existing Irish housing stock, using the only existing housing database which also represents the only source of available background data for the thesis. A significant proportion of the housing stock was found to be lacking necessary energy efficiency measures, a likely result of the gap in the delay in introducing mandatory building regulations when they were built. For example, Oil represents the main fuel used for heating in Irish housing, and only 27% of houses have floor insulation.

However, despite the availability of various financial incentives including information/education, to support energy efficiency improvements, residential energy consumption and emissions have been on the increase over the years. It is likely that future energy efficiency upgrades in the existing Irish housing stock will rely on regulation and enforcement including improved performance of the non-regulatory measures. A clear strategy is clearly needed to carry out improvements of the housing stock, especially when compared to similar housing stocks in EU. The inventory of the retrofit measures that required to be focused on includes fabric upgrade (application of sealing to the thermal envelope of the building, external and internal insulation, ceiling insulation, rafter insulation, floor insulation, replacement of windows and insulation of new solid doors), heating system upgrades, and application of micro-generation devices.

This thesis presents the development of a model that can aid decisions, and cost effective as one of the most effective ways to complement mitigation effort in energy and emission reductions. The model comprises the developed archetype model (earlier mentioned), an energy model and an LCA software tool, and has been applied to the existing Irish housing and validated with statistics and previous studies. The study focuses on retrofit measures that are within the contemporary obtainable practices, and in particular the examples of feasible retrofits identified from literature. The results of the energy and emissions analyses show that reducing operational energy becomes intractable due to the poor quality of many of the representative archetype houses. This is most common with detached houses. In summary:

- For the BaseCase scenario, operational energy/emission remains dominant for all archetypes when compared with other life cycle phases. Overall, detached houses display higher operational energy use, mainly a result of the higher floor and window areas including the use of oil-fired boilers. Maintenance and disassembly phases are of minor significance. The weighted average dwelling is responsible for 45, 478kWh/yr operational energy consumption, which is found to be consistent with national statistics, especially when all relevant upstream processes in the supply and production of fuels that occurred in Ireland and abroad are considered. The weighted average dwelling operational energy consumption can be reduced by 51% and 75% in the Current Regulations and Passive House standard scenarios, respectively compared to the BaseCase scenario. Another comparison between the Current Regulations and Passive House standard scenarios indicates that the weighted average dwelling operational energy consumption can be reduced by 47.6% relative to the Current Regulations scenario. The cumulative embodied energy for most archetypes is at least 0.24%, 4.8% and 10.3% of the life cycle's total in the BaseCase, Current Regulations and Passive House standard scenarios, respectively.

- The proportion of international sources of operational energy consumption by the weighted average dwelling represents 5,930kWh/yr (13%) of the life cycle's total in the BaseCase scenario. However, this can be reduced by 61.7% and 72.4% in the Current Regulations and Passive House standard scenarios, respectively. Similarly, retrofitting from Current Regulations scenario to Passive House standard scenario will result in 27.8% savings in energy attributable to imported fossil fuels.

- The result shows that the archetype stock model estimates residential sector total national operational primary energy-related emissions to be 9,447ktCO_2-eq. in 2005. This figure is found to be consistent with national statistics, especially when all relevant upstream processes in the supply and production of fuels that occurred in Ireland and abroad are considered. National operational primary energy-related emissions can be reduced by 50%, 73% and 46% in the Current Regulations, Passive House and Current Regulations vs. Passive House scenarios, respectively. For the BaseCase scenario, detached houses display the highest national operational emissions (6,487ktCO_2-eq.), followed by semi-detached house/end-terraced house archetypes (1,519ktCO_2-eq.) and mid-terraced house/apartment archetypes (1,442ktCO_2-eq.), respectively. National operational primary energy-related emissions for detached houses, semi-detached house/end-terraced house archetypes and mid-terraced house/apartment archetypes can be reduced by 54%, 76%, 47.4%; 38%, 66%, 41.5%; and 47%, 69%, 45.5% in the Current Regulations, Passive House, and Current Regulations vs. Passive House scenarios, respectively.

- The results show that the archetype stock model estimates national life cycle emissions for the BaseCase, scenario to be 9,838ktCO_2-eq. National life cycle primary energy-related emissions can be reduced by 43%, 84.7% and 28% in the Current Regulations, Passive House and Current Regulations vs. Passive House scenarios, respectively. National operational primary energy-related emissions for detached houses, semi-detached house/end-terraced house archetypes and mid-terraced house/apartment archetypes can be reduced by 47.6%, 64.5%, 32%; 27.7%, 49%, 29.7%; and 39.5%, 45%, 9.6% in the Current Regulations, Passive House, and Current Regulations vs. Passive House scenarios, respectively.

- The BaseCase scenario has the lowest range of life cycle costs (LCC) for all archetypes as they were not retrofitted. This is followed by: Current Regulations scenario; retrofitting from the Current Regulations scenario to the Passive House scenario; and Passive House scenarios, respectively. Detached houses show the highest range of LCC for all archetypes for the BaseCase scenario, mainly a result of the use of oil compared to the other dwelling types that are running on gas. Overall, detached houses show the highest range of LCC for the retrofitted scenarios. This is followed by semi-detached house/end-terraced house archetypes and mid-terraced house/apartment archetypes, respectively. As the archetype dwelling type with the lowest discounted LCC will be accepted as most cost effective, one could come to the conclusion that if the decision is to maintain rather than renovate, semi-detached house/end-terraced house archetypes would be first choice, followed by mid-terraced house/apartment archetypes, especially with limited available funding. As the model indicates that the more energy efficient the scenario the higher the LCC, if the decision is to renovate within limited funding, one could conclude that detached house archetypes present a good choice in the Current Regulations scenario. However, with adequate funding, it is suggested that renovation of detached houses should be carried out based on: Passive House scenario; and retrofitting from Current Regulations scenario to the Passive House scenario, in that hierarchical order of importance, especially when considered in line with the CO_2 abatement potential identified in the environmental impact results and in line with the main aim of this study.

- The abatement opportunity in 2055 is greater in terms of costs and emissions savings than for the year 2020 for all retrofitted scenarios. The 2020 high retrofitting costs to society is mainly due to low emissions savings as most investments put into energy efficiency improvement projects in the year 2020 are also meant for the year 2055. Detached houses provide the least retrofit costs as well as the highest emissions savings for both years 2020 and 2055 for all retrofitted scenarios. This thesis has shown that a total of 76MtCO_2-eq, 104.2MtCO_2-eq and 21.2MtCO_2-eq savings could be met at retrofitting abatement costs of €592/tCO_2-eq, €741/tCO_2-eq and €1,141/tCO_2-eq by 2020 in the Current Regulations, Passive House Regulations, and Current Regulations vs. Passive House Regulations comparison, respectively.

Similarly, emissions reductions for 2055 are estimated to be 211MtCO_2-eq, 289.6MtCO_2-eq and 78.7MtCO_2-eq at retrofitting costs of €148/tCO_2-eq, €200/tCO_2-eq and €341/tCO_2-eq by 2055 in the Current Regulations, Passive House Regulations, and Current Regulations vs. Passive House Regulations comparison, respectively.

Finally, this thesis has shown that the hybrid-LCA developed can be used to analyse a holistic view of the energy and emissions attributable to the existing Irish housing stock. The thesis has also made recommendations on how best to retrofitting the housing stock.

The study further leads to the following conclusions for 2020 and 2055:

Overall, in comparison to other studies within the same climatic zone, the higher operational energy reflects the mostly energy-inefficient housing stock. The retrofit and maintenance phases at archetype level are significant for all retrofit scenarios. The disassembly phase is of little significance.

The development of the hybrid model used in this study can be applied in other countries using the respective sector and sub-sector energy/emissions intensities. The hybrid technique used in calculating the portion of international arising emissions and emissions due to services (emissions from national sources) can form part of the contributions required to complement the existing technological and environmental mechanisms (i.e. LCI and LCIA) in LCA.

7.2 Further research

Further research should be promoted to look into the harmonization of the existing hybrid methodologies for LCA, especially with a view to integrating the already existing technological and environmental data with economic data. Along this continuum, such a study should also look into the potential for data improvement, especially for domestic production of materials and services.

As the energy performance of dwellings increases through retrofitting the proportion of the embodied energy becomes a greater factor in the national environmental total balance. Using low-CO_2 intensive materials and substituting materials of disassembly for virgin materials can assist in reducing both operational and embodied energy. This study therefore proposes the promotion of a further research to look into the above aspect. Such a study can provide additional data information directed towards experts in environmental policy. Data from such a study can assist in improving national database as well as reducing barriers to collection and gathering of data regarding embodied energy.

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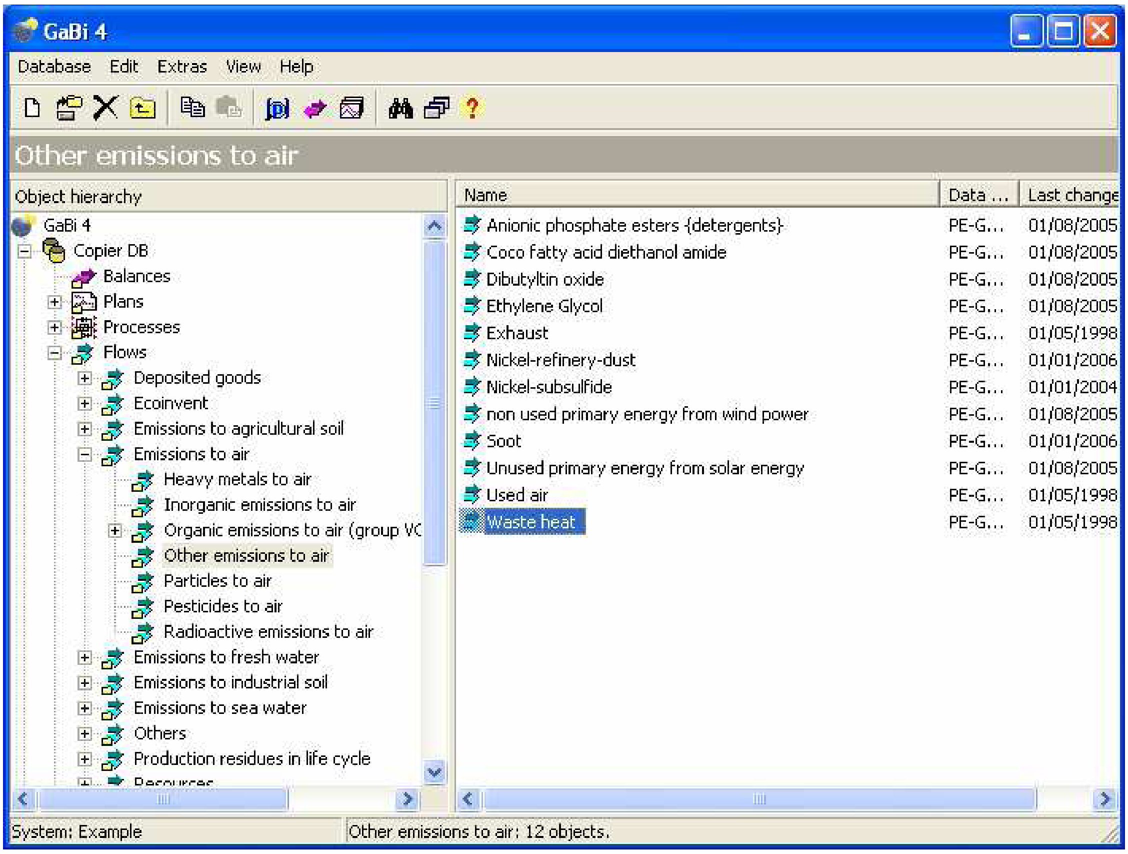
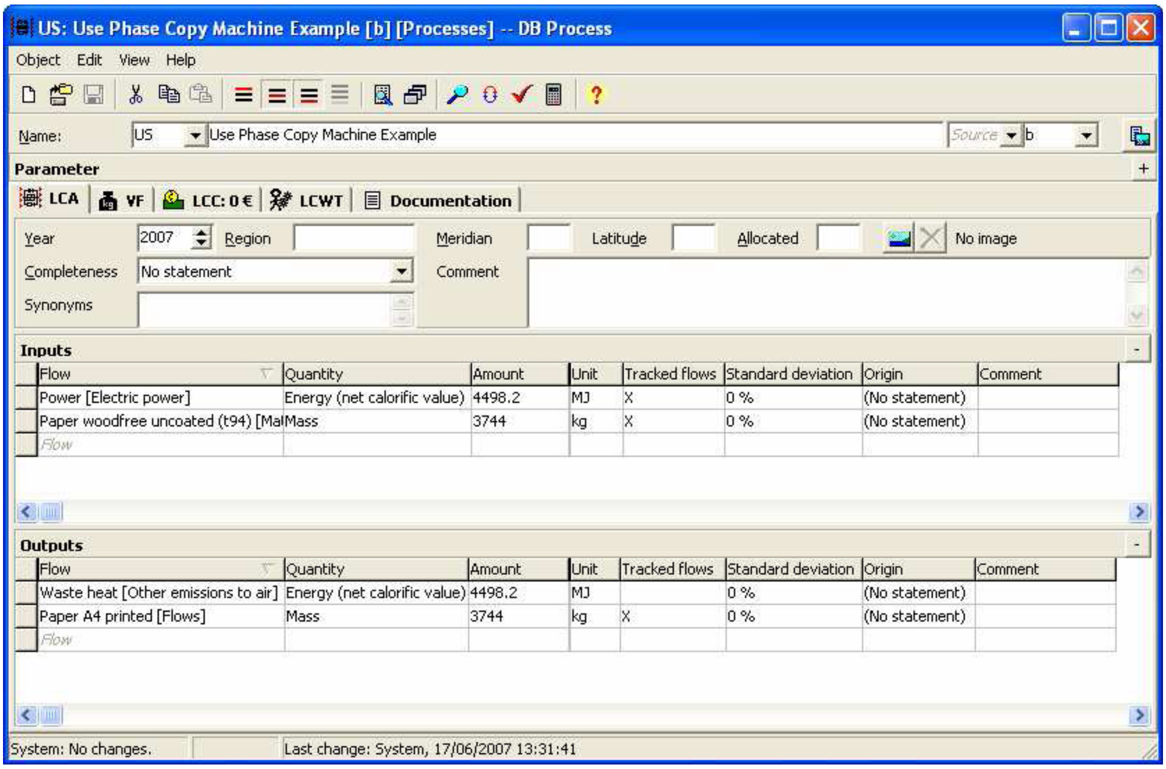
List of Appendices

Appendix 1: GaBi applications – Flows, Processes, Plans and Balances

1. **GaBi 4 sample: DB manager showing flows from which process plans are developed (PE International, 2009).**

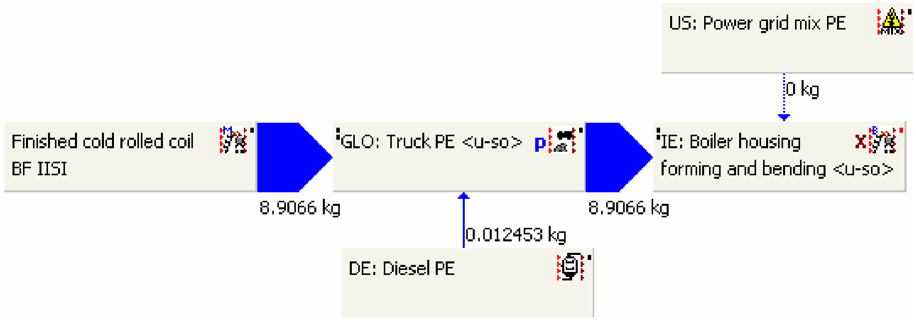


2. **GaBi 4 sample DB manager process (PE International, 2009).**

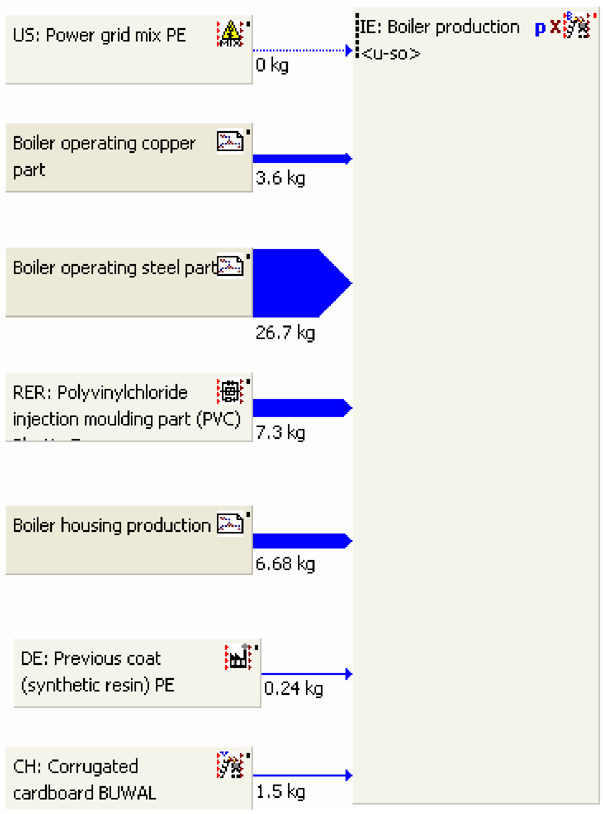


3. **GaBi 4.4 selected process sample for grid electricity (PE International, 2009) – similar are used in building study processes and plans.**

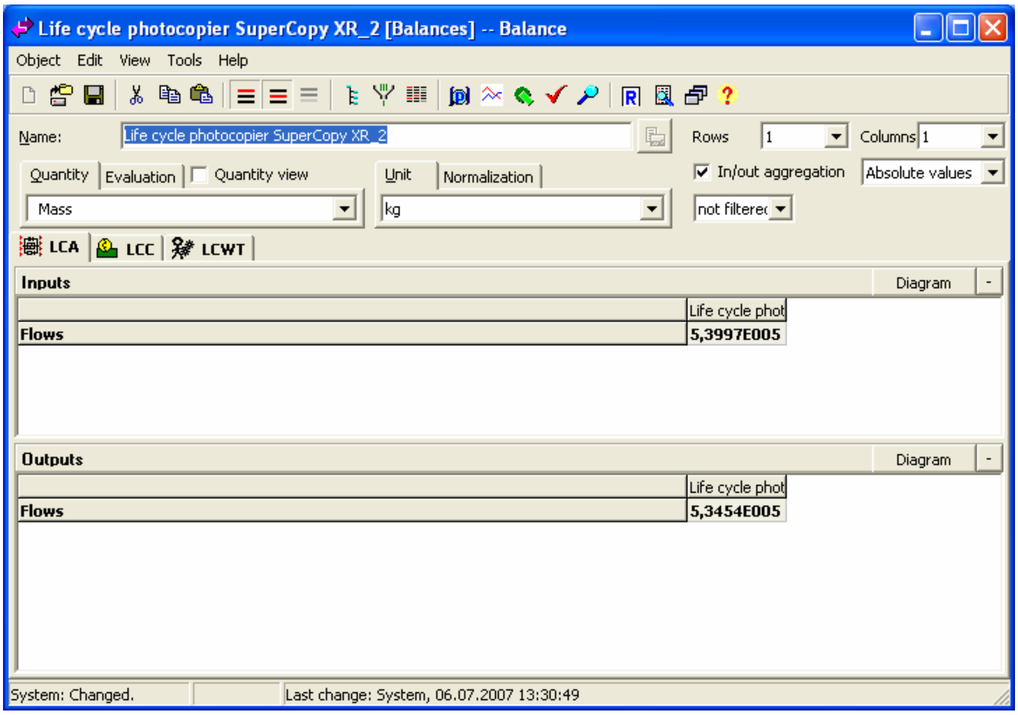
4. **Study assembly of processes to depict a sub-stage (boiler housing) of the building system**



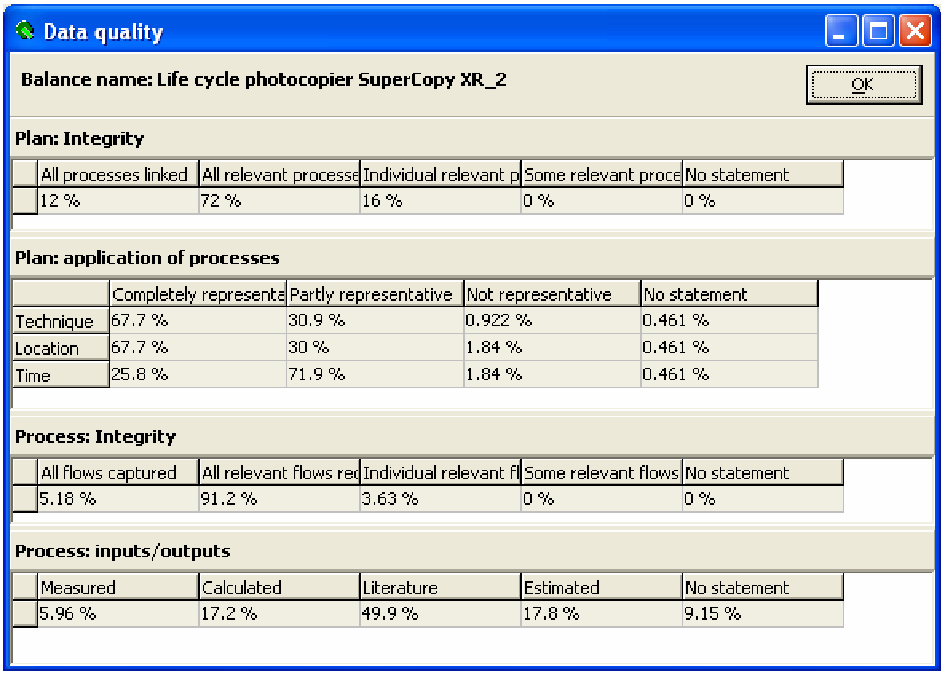
5. **Study assembly of chain of processes and sub-plans to depict a stage (conventional boiler) of the building system.**



6. **Sample GaBi window balance (PE International, 2009).**

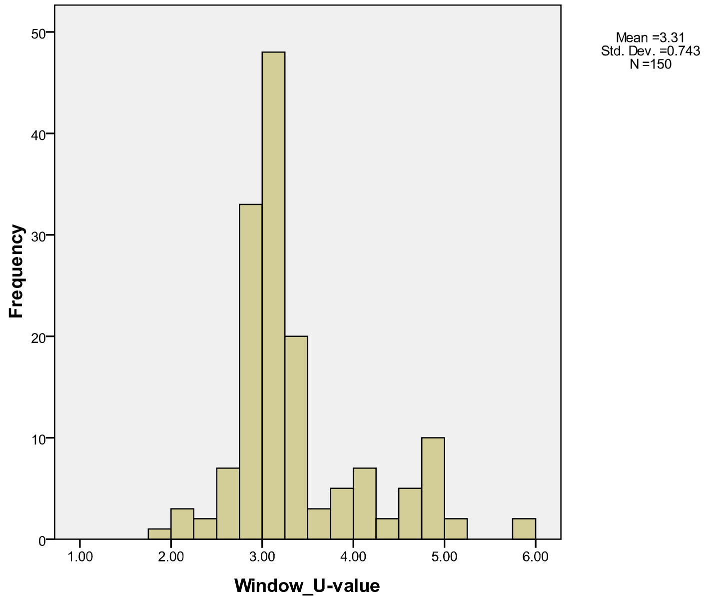


7. **GaBi 4 sample - Data quality in balances (PE International, 2009**

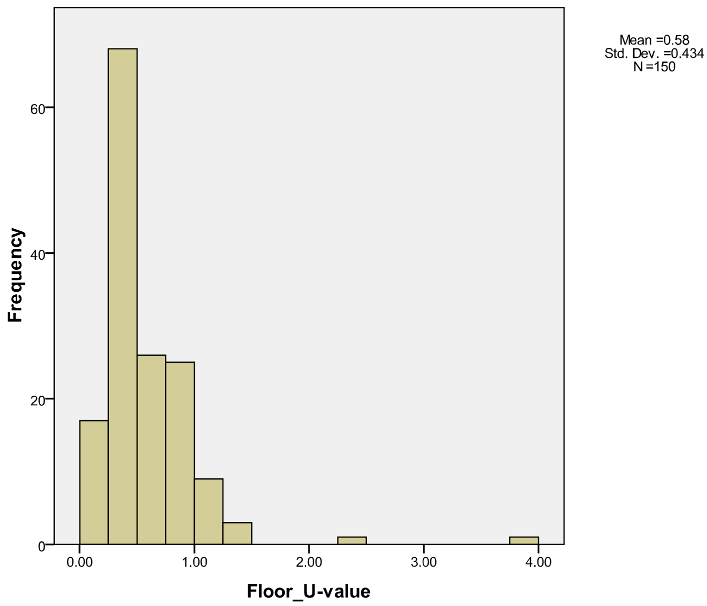


Appendix 2: Archetype development graphs

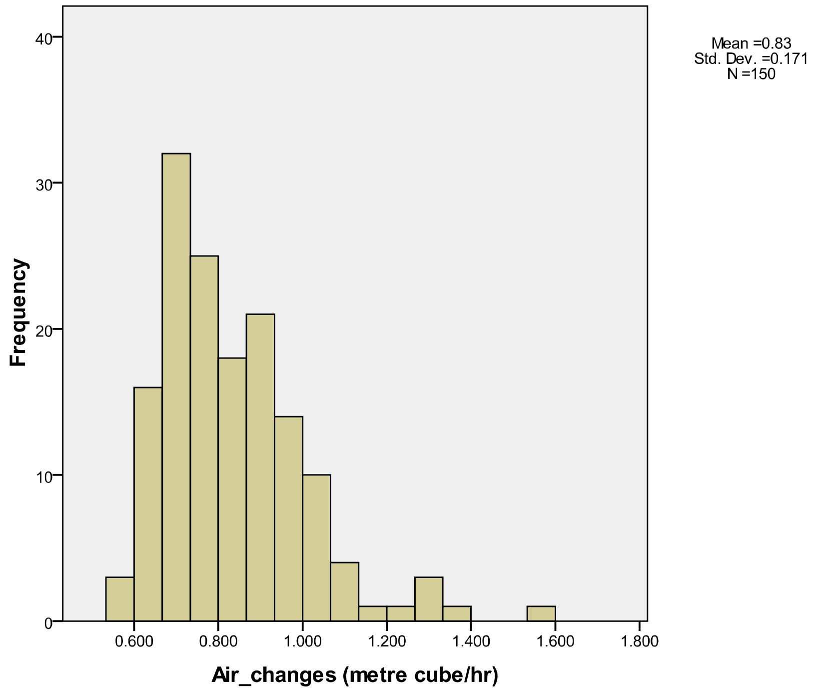
1. Frequency histogram of window construction type



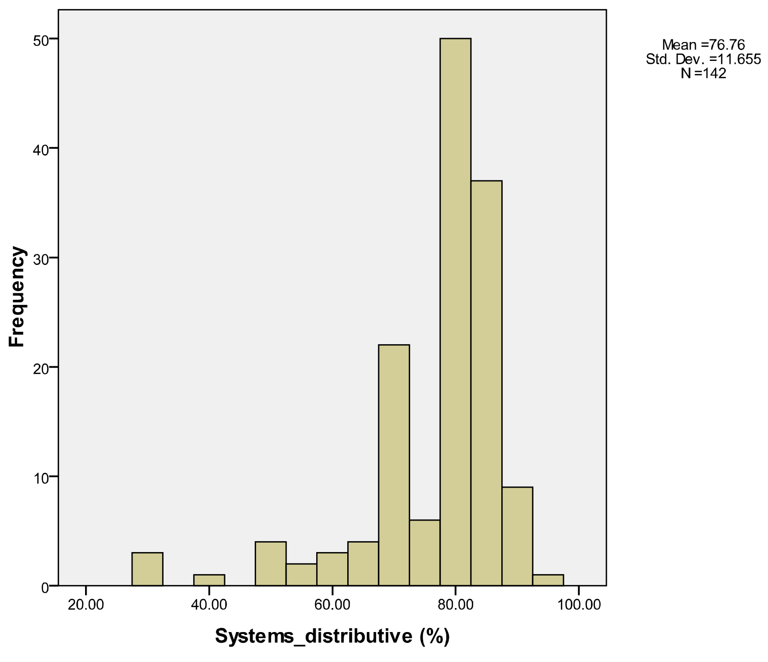
2. Frequency histogram of floor costruction type



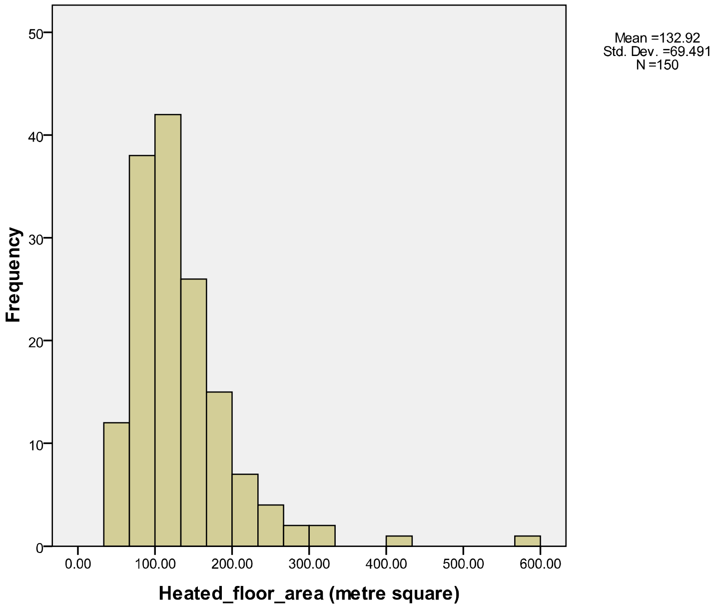
3. Frequency histogram of air changes



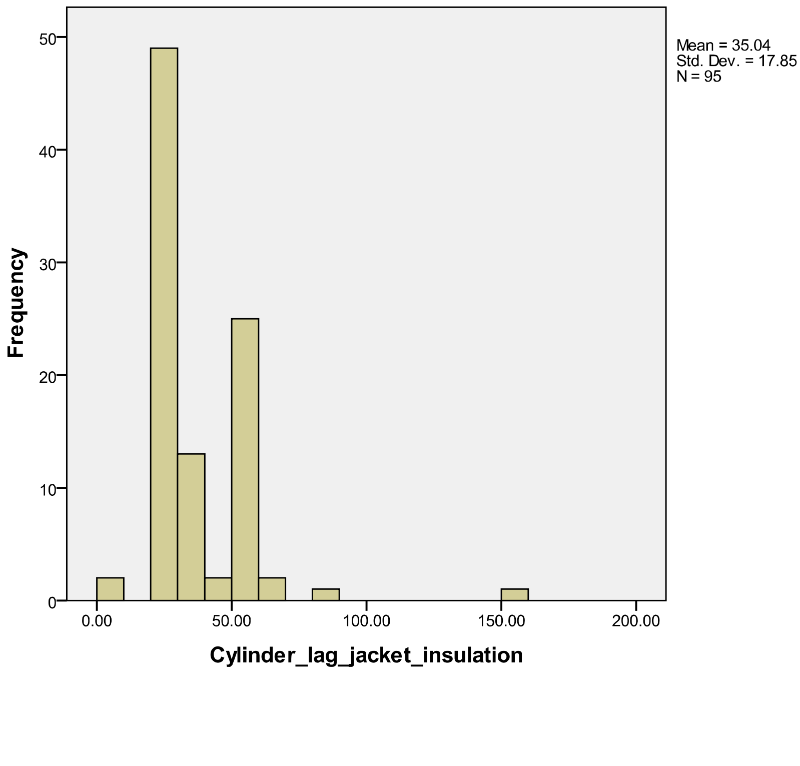
4. Frequency histogram of heating system efficiency



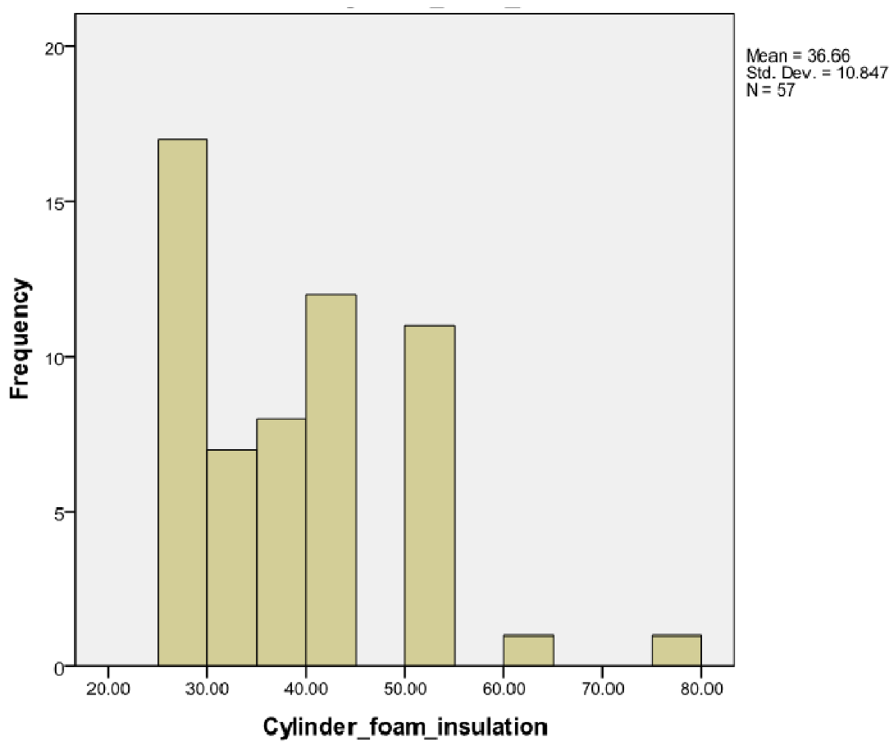
5. Frequency histogram of heated floor area



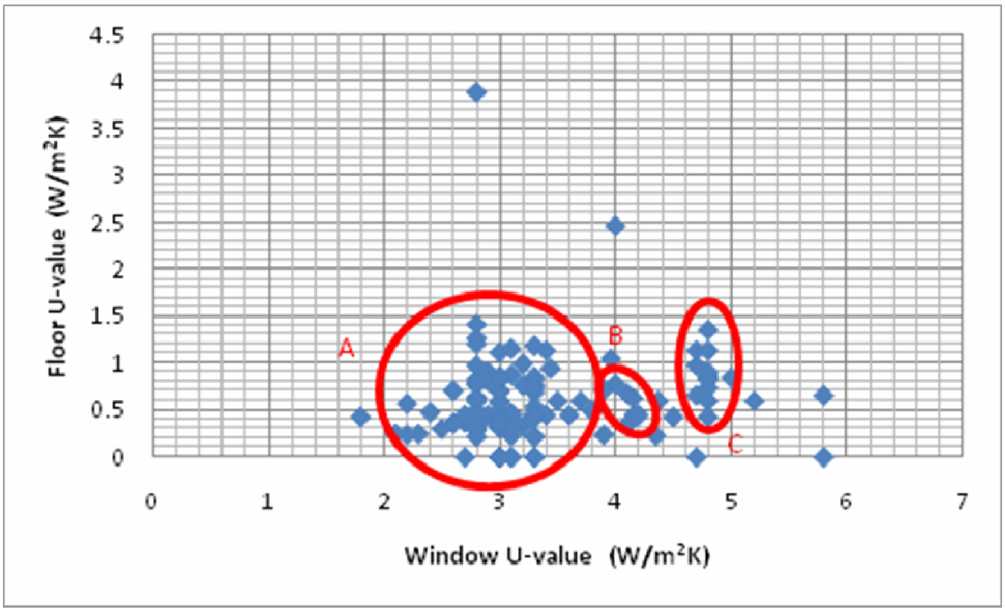
6. Frequency histogram of Cylinder lagging jacket insulation



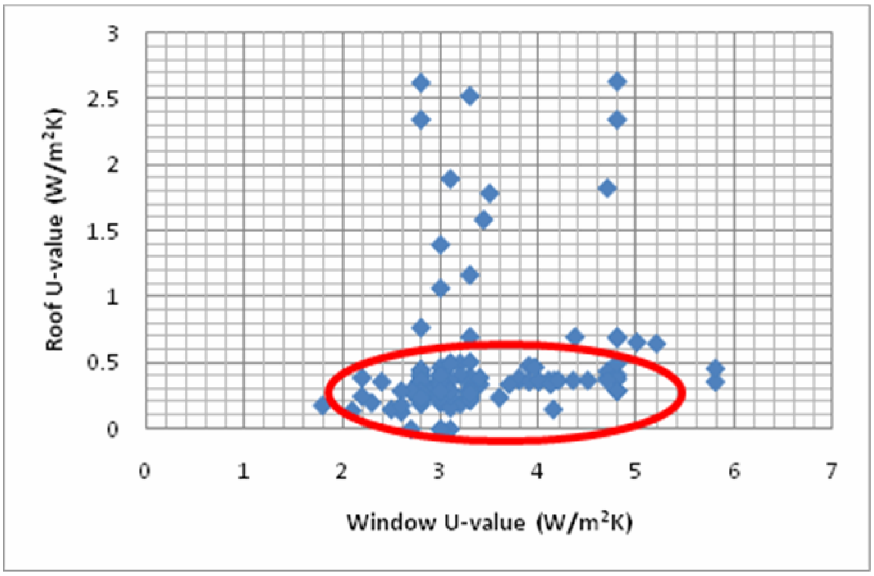
7. Frequency histogram of Cylinder factory-applied PU foam insulation



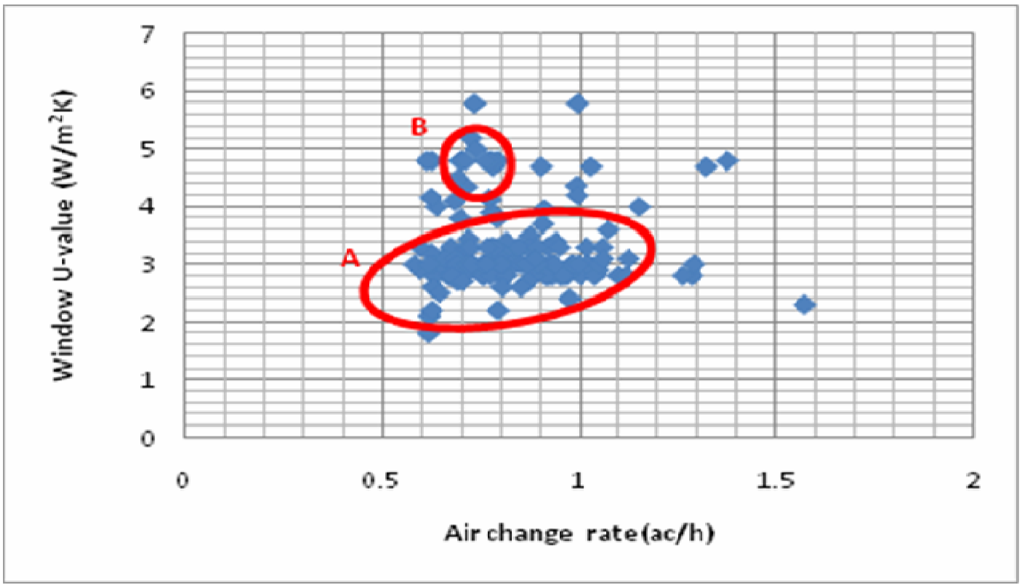
8. Scatter plot: Window vs. floor construction types



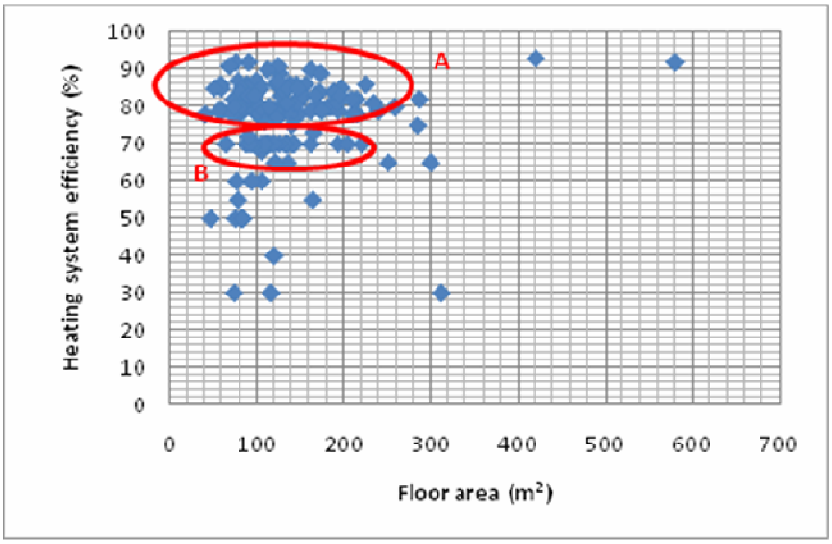
9. Scatter plot: Window U-value vs. roof construction types



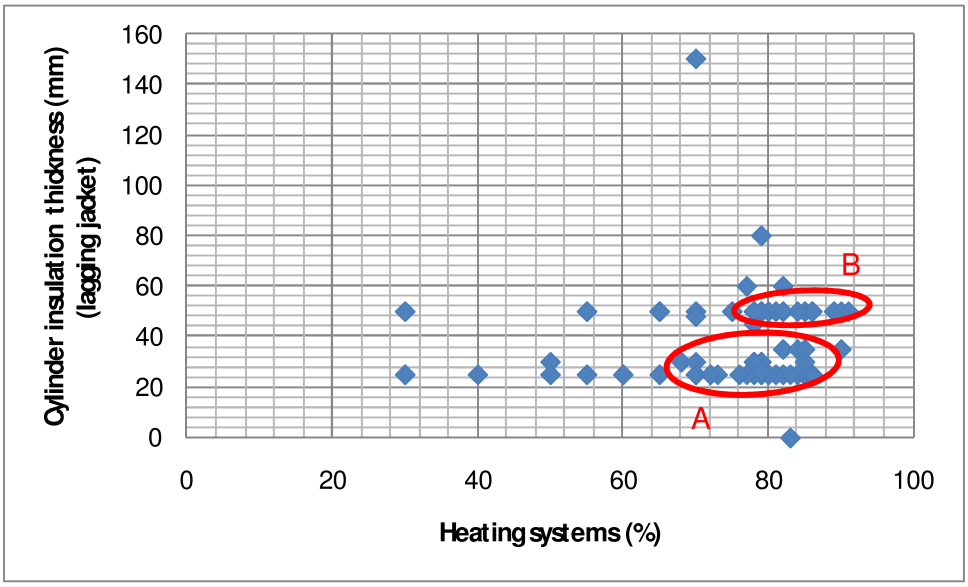
10. Scatter plot: Air change rate vs. window U-values construction types



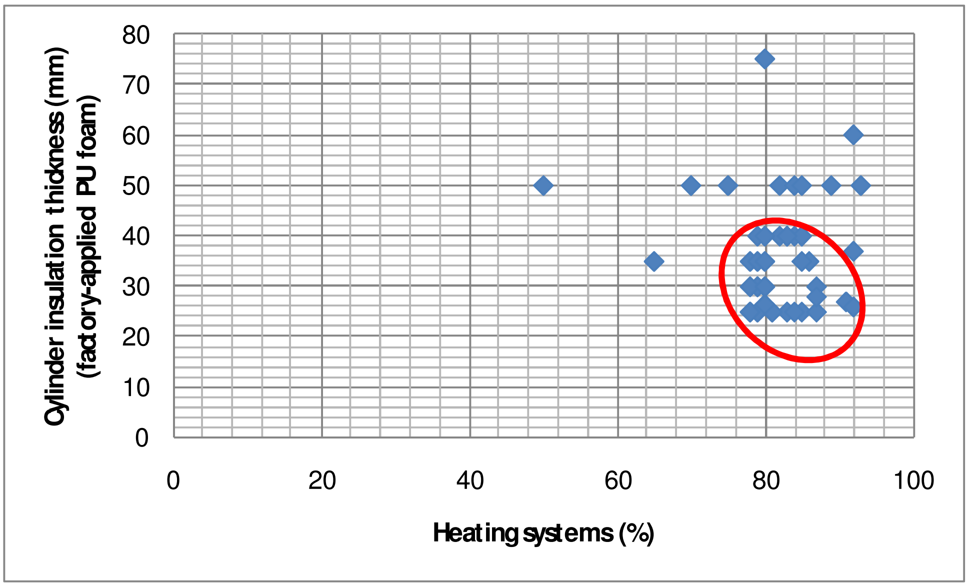
11. Scatter plot: Floor U-values vs. heating system efficiency construction types



12. Scatter plot: Heating system vs. DHW cylinder insulation (lagging jacket) construction details



13. Scatter plot: Heating system vs. DHW cylinder insulation (factory-applied PU foam) construction details



Appendix 3: Representative archetype house materials list

Archetype 1: Materials list

Material	**Kg**
Ready-mix concrete	**24,273**
Cement screed (floor screed)	**3,990**
Mortar	**7,722**
Masonry mortar	2,122
Light weight mortar	5,600
Cement	**180**
Concrete block	**33,300**
Light weight concrete block	33,300
Roof tile	**2,175**
Concrete roof tile	2,175
Clay roof tile	0
Brick	**2,600**
Light weight brick	2,600
Metal	**1,127**
Copper	335
Galvanised steel	582
Steel metal	210
Wood	**2,025**
plywood	0
Roof timber	800
Wood product (door and flooring)	1,200
Wood packaging	25
Gypsum plasterboard	**1,330**
Insulation	**1,565**
Quilt (for wall)	480
Quilt (for roof)	766
Polyurethane foam (for floor)	319
Ceramic tiles (12 and 10m^2 of tiles for wall and floor, respectively)	**110**
Sanitary wares	**89**
Polymers	**988.6**
Paint	48
Polyethylene granulate, PE	0
Polyethylene, film	180
Polyvinyl chloride granulate(PVC)	672.6
Sealant	88
General	0
Glass products (valuable substances)	**502.5**
Corrugated board	**120**
Lighting products and electrical installation	**338**
Appliances	**250**
Total	**82,575.1**

Appendix 4: Tables and graphs for upgrade measures

1. Detailed description of the retrofit measures applied to archetype 2 relative to the BaseCase house option

Archetype 2		Scenario		
		BaseCase	**Current Regulations**	**Passive house standard**
Materials	**Building element**	**Existing information as above**	**Derivation of new retrofit measures relative to the BaseCase scenario**	
Mineral wool (slab)	Wall insulation	75(mm, thick)	382 kg	742 kg
Mineral wool (quilt)	Roof insulation	100 (mm, thick)	294 kg	514 kg
Polyurethane rigid foam insulation	Ground floor	43(mm, thick)	307 kg	587 kg
Polyurethane rigid foam insulation	DHW cylinder insulation	30* (mm, thick)	1.2 kg	2.7 kg
Polyurethane rigid foam insulation	Door insulation	0	3.53 kg	3.53 kg
	Air change rate	0.74ac/h	0.35 ac/h	0.25 ac/h
	Windows	Double-glazing	Triple-glazing (1 low-emissivity coating, 2 gaps with air to achieve a U-value of 1.6.)	Triple-glazing (1 low- emissivity coating, 2 gaps with argon gas, and integral draught proofing/stripping, to achieve a U-value of 0.8 (Gustavsson, 2010))
Not available	H/system	Conventional oil boiler	Condensing boiler, Solar hot water - 4m^2 solar flat plate system	Ground source heat pump (Gshp), Solar hot water - 4m^2 solar flat plate system, Mechanical ventilation plus heat recovery (MVHR) and PV system

*DHW cylinder lagging jacket

Description of representative variables

Variable (m^2)	Quantity
Wall area	144
Roof area	141
Floor area	133
DHW insulation area	2
Window size	29

2. Detailed description of the retrofit measures applied to archetype 3 relative to the BaseCase scenario

Archetype 3		Scenario		
		BaseCase	**Current Regulations**	**Passive house standard**
Materials	**Building element**	**Existing information as above**	**Derivation of new retrofit measures relative to the BaseCase scenario**	
Mineral wool (slab)	Wall insulation	75(mm, thick)	290 kg	561 kg
Mineral wool (quilt)	Roof insulation	100 (mm, thick)	273.5 kg	478 kg
Polyurethane rigid foam insulation	Ground floor	43 (mm, thick)	307 kg	587 kg
Polyurethane rigid foam insulation	DHW cylinder insulation	30*(mm, thick)	1.2 kg	2.7 kg
Polyurethane rigid foam insulation	Door insulation	0	3.53 kg	3.53 kg
	Air change rate	0.67ac/h	0.35 ac/h	0.25 ac/h
	Windows	Single-glazing	Triple-glazing (1 low-emissivity coating, 2 gaps with air to achieve a U-value of 1.6.)	Triple-glazing (1 low- emissivity coating, 2 gaps with argon gas, and integral draught proofing/stripping, to achieve a U-value of 0.8 (Gustavsson, 2010))
	H/system	Conventional oil boiler	Condensing boiler, Solar hot water - 4m^2 solar flat plate system	Ground source heat pump (Gshp), Solar hot water - 4m^2 solar flat plate system, Mechanical ventilation plus heat recovery (MVHR) and PV system

*DHW cylinder lagging jacket

Description of representative variables

Variable (m^2)	Quantity
Wall area	109
Roof area	131
Floor area	133
DHW insulation area	2
Window size	28

3. **Detailed description of the retrofit measures applied to archetype 4 relative to the BaseCase scenario**

Archetype 4		Scenario		
		BaseCase	**Current Regulations**	**Passive House standard**
Materials	**Building element**	**Existing information as above**	**Derivation of new retrofit measures relative to the BaseCase scenario**	
Mineral wool (slab)	Wall insulation	75(mm, thick)	312.7 kg	607.7 kg
Mineral wool (quilt)	Roof insulation	110 (mm, thick)	448 kg	812 kg
Polyurethane rigid foam insulation	Ground floor	43 (mm, thick)	307 kg	587 kg
Polyurethane rigid foam insulation	DHW cylinder insulation	37 (mm, thick)	0.78 kg	2.28 kg
Polyurethane rigid foam insulation	Door insulation	0	3.53 kg	3.53 kg
	Air change rate	0.87ac/h	0.35 ac/h	0.25 ac/h
	Windows	Double-glazing	Triple-glazing (1 low-emissivity coating, 2 gaps with air to achieve a U-value of 1.6.)	Triple-glazing (1 low- emissivity coating, 2 gaps with argon gas, and integral draught proofing/stripping, to achieve a U-value of 0.8 (Gustavsson, 2010))
	H/system	Conventional oil boiler	Condensing boiler, Solar hot water - 4m2 solar flat plate system	Ground source heat pump (Gshp), Solar hot water - 4m^2 solar flat plate system, Mechanical ventilation plus heat recovery (MVHR) and PV system

Description of representative variables

Variable (m^2)	Quantity
Wall area	118
Roof area	112
Floor area	133
DHW insulation area	2
Window size	16

4. Detailed description of the retrofit measures applied to archetype 5 relative to the BaseCase

Archetype 5		Scenario		
		BaseCase	**Current Regulations**	**Passive House standard**
Materials	**Building element**	**Existing information as above**	**Derivation of new retrofit measures relative to the BaseCase scenario**	
Mineral wool (slab)	Wall insulation	75(mm, thick)	551 kg	1071 kg
Mineral wool (quilt)	Roof insulation	110 (mm, thick)	427 kg	769 kg
Polyurethane rigid foam insulation	Ground floor	43 (mm, thick)	307 kg	587 kg
Polyurethane rigid foam insulation	DHW cylinder insulation	35 (mm, thick)	0.9 kg	2.4 kg
Polyurethane rigid foam insulation	Door insulation	0	3.53 kg	3.53 kg
	Air change rate	0.74ac/h	0.35 ac/h	0.25 ac/h
	Windows	Double-glazing	Triple-glazing (1 low-emissivity coating, 2 gaps with air to achieve a U-value of 1.6.)	Triple-glazing (1 low-emissivity coating, 2 gaps with argon gas, and integral draught proofing/stripping, to achieve a U-value of 0.8 (Gustavsson, 2010))
	H/system	Conventional oil boiler	Condensing boiler, solar hot water - 4m2 solar flat plate system	Ground source heat pump (Gshp), Solar hot water - 4m^2 solar flat plate system, Mechanical ventilation plus heat recovery (MVHR) and PV system

Description of representative variables

Variable (m^2)	Quantity
Wall area	208
Roof area	106
Floor area	133
DHW insulation area	2
Window size	46

5. Detailed description of the retrofit measures applied to archetype 6 relative to the BaseCase scenario

Archetype 6		Scenario		
		BaseCase	**Current standard**	**Passive house standard**
Materials	**Building element**	**Existing information as above**	**Derivation of new retrofit measures relative to the BaseCase scenario**	
Mineral wool (slab)	Wall insulation	100(mm, thick)	378 kg	851 kg
Mineral wool (quilt)	Roof insulation	135 (mm, thick)	246 kg	483 kg
Polyurethane rigid foam insulation	Ground floor	50(mm, thick)	279 kg	559 kg
Polyurethane rigid foam insulation	DHW cylinder insulation	37 (mm, thick)	0.78 kg	2.28 kg
Polyurethane rigid foam insulation	Door insulation	0	3.53 kg	3.53 kg
	Air change rate	0.67ac/h	0.35 ac/h	0.25 ac/h
	Windows	Double-glazing	Triple-glazing (1 low-emissivity coating, 2 gaps with air to achieve a U-value of 1.6.)	Triple-glazing (1 low- emissivity coating, 2 gaps with argon gas, and integral draught proofing/stripping, to achieve a U-value of 0.8 (Gustavsson, 2010))
	H/system	Conventional oil boiler	Condensing boiler, Solar hot water - 4m2 solar flat plate system	Ground source heat pump (Gshp), Solar hot water - $4m^2$ solar flat plate system, Mechanical ventilation plus heat recovery (MVHR) and PV system

Description of representative variables

Variable (m^2)	Quantity
Wall area	189
Roof area	152
Floor area	133
DHW insulation area	2
Window size	42

6. Detailed description of the retrofit measures applied to archetype 7 relative to the BaseCase scenario

Archetype 7		Scenario		
		BaseCase	**Current Regulations**	**Passive House standard**
Materials	**Building element**	**Existing information as above**	**Derivation of new retrofit measures relative to the BaseCase scenario**	
Mineral wool (slab)	Wall insulation	75(mm, thick)	231 kg	448 kg
Mineral wool (quilt)	Roof insulation	135 (mm, thick)	89 kg	175 kg
Polyurethane rigid foam insulation	Ground floor	50(mm, thick)	210 kg	420 kg
Polyurethane rigid foam insulation	DHW cylinder insulation	35 (mm, thick)	0.9 kg	2.4 kg
Polyurethane rigid foam insulation	Door insulation	0	3.53 kg	3.53 kg
	Air change rate	0.94ac/h	0.35 ac/h	0.25 ac/h
	Windows	Double-glazing	Triple-glazing (1 low-emissivity coating, 2 gaps with air to achieve a U-value of 1.6.)	Triple-glazing (1 low- emissivity coating, 2 gaps with argon gas, and integral draught proofing/stripping, to achieve a U-value of 0.8 (Gustavsson, 2010))
	H/system	Conventional oil boiler	Condensing boiler, Solar hot water - 4m2 solar flat plate system	Ground source heat pump (Gshp), Solar hot water - 4m^2 solar flat plate system, Mechanical ventilation plus heat recovery (MVHR) and PV system

Description of representative variables

Variable (m^2)	Quantity
Wall area	87
Roof area	55
Floor area	100
DHW insulation area	2
Window size	17

7. Detailed description of the retrofit measures applied to archetype 8 relative to the BaseCase scenario

Archetype 8		Scenario		
		BaseCase	**Current Regulations**	**Passive House standard**
Materials	**Building element**	**Existing information as above**	**Derivation of new retrofit measures relative to the BaseCase scenario**	
Mineral wool (slab)	Wall insulation	70(mm, thick)	241 kg	469 kg
Mineral wool (quilt)	Roof insulation	140 (mm, thick)	84.2 kg	165 kg
Polyurethane rigid foam insulation	Ground floor	50(mm, thick)	210 kg	420 kg
Polyurethane rigid foam insulation	DHW cylinder insulation	50* (mm, thick)	0 kg	1.5 kg
Polyurethane rigid foam insulation	Door insulation	0	3.53 kg	3.53 kg
	Air change rate	0.94ac/h	0.35 ac/h	0.25 ac/h
	Windows	Double-glazing	Triple-glazing (1 low-emissivity coating, 2 gaps with air to achieve a U-value of 1.6.)	Triple-glazing (1 low- emissivity coating, 2 gaps with argon gas, and integral draught proofing/stripping, to achieve a U-value of 0.8 (Gustavsson, 2010))
	H/system	Conventional oil boiler	Condensing boiler, Solar hot water - 4m2 solar flat plate system	Ground source heat pump (Gshp), Solar hot water - $4m^2$ solar flat plate system, Mechanical ventilation plus heat recovery (MVHR) and PV system

*DHW cylinder lagging jacket

Description of representative variables

Variable (m^2)	Quantity
Wall area	91
Roof area	52
Floor area	100
DHW insulation area	2
Window size	16

8. Detailed description of the retrofit measures applied to archetype 9 relative to the BaseCase scenario

Archetype 9		Scenario		
		BaseCase	**Current Regulations**	**Passive House standard**
Materials	**Building element**	**Existing information as above**	**Derivation of new retrofit measures relative to the BaseCase scenario**	
Mineral wool (slab)	Wall insulation	70(mm, thick)	252 kg	489 kg
Mineral wool (quilt)	Roof insulation	110 (mm, thick)	109 kg	198 kg
Polyurethane rigid foam insulation	Ground floor	50(mm, thick)	210 kg	420 kg
Polyurethane rigid foam insulation	DHW cylinder insulation	30* (mm, thick)	1.2 kg	2.7 kg
Polyurethane rigid foam insulation	Door insulation	0	3.53 kg	3.53 kg
	Air change rate	0.87ac/h	0.35 ac/h	0.25 ac/h
	Windows	Double-glazing	Triple-glazing (1 low-emissivity coating, 2 gaps with air to achieve a U-value of 1.6.)	Triple-glazing (1 low- emissivity coating, 2 gaps with argon gas, and integral draught proofing/stripping, to achieve a U-value of 0.8 (Gustavsson, 2010))
	H/system	Conventional oil boiler	Condensing boiler, Solar hot water - 4m2 solar flat plate system	Ground source heat pump (Gshp), Solar hot water - 4m^2 solar flat plate system, Mechanical ventilation plus heat recovery (MVHR) and PV system

*DHW cylinder lagging jacket

Description of representative variables

Variable (m^2)	Quantity
Wall area	95
Roof area	57
Floor area	100
DHW insulation area	2
Window size	16

9. Detailed description of the retrofit measures applied to archetype 10 relative to the BaseCase scenario

Archetype 10		Scenario		
		BaseCase	Current standard	Passive house standard
Materials	**Building element**	**Existing information as above**	**Derivation of new retrofit measures relative to the BaseCase scenario**	
Mineral wool (slab)	Wall insulation	70(mm, thick)	215 kg	417 kg
Mineral wool (quilt)	Roof insulation	140 (mm, thick)	92.3 kg	181 kg
Polyurethane rigid foam insulation	Ground floor	50 (mm, thick)	210 kg	420 kg
Polyurethane rigid foam insulation	DHW cylinder insulation	40(mm, thick)	0.9 kg	2.4kg
Polyurethane rigid foam insulation	Door insulation	0	3.53 kg	3.53 kg
	Air change rate	0.94ac/h	0.35 ac/h	0.25 ac/h
	Windows	Double-glazing	Triple-glazing (1 low-emissivity coating, 2 gaps with air to achieve a U-value of 1.6.)	Triple-glazing (1 low- emissivity coating, 2 gaps with argon gas, and integral draught proofing/stripping, to achieve a U-value of 0.8 (Gustavsson, 2010))
	H/system	Conventional oil boiler	Condensing boiler, Solar hot water - 4m2 solar flat plate system	Ground source heat pump (Gshp), Solar hot water - 4m^2 solar flat plate system, Mechanical ventilation plus heat recovery (MVHR) and PV system

Description of representative variables

Variable (m^2)	Quantity
Wall area	81
Roof area	57
Floor area	100
DHW insulation area	2
Window size	15

10. Detailed description of the retrofit measures applied to archetype 11 relative to the BaseCase scenario

Archetype 11		Scenario		
		BaseCase	**Current Regulations**	**Passive House standard**
Materials	**Building element**	**Existing information as above**	**Derivation of new retrofit measures relative to the BaseCase scenario**	
Mineral wool (slab)	Wall insulation	75(mm, thick)	122 kg	237 kg
Mineral wool (quilt)	Roof insulation	135 (mm, thick)	76 kg	150 kg
Polyurethane rigid foam insulation	Ground floor	50(mm, thick)	210 kg	420 kg
Polyurethane rigid foam insulation	DHW cylinder insulation	30*(mm, thick)	1.2 kg	2.7kg
Polyurethane rigid foam insulation	Door insulation	0	3.53 kg	3.53 kg
	Air change rate	0.87ac/h	0.35 ac/h	0.25 ac/h
	Windows	Double-glazing	Triple-glazing (1 low-emissivity coating, 2 gaps with air to achieve a U-value of 1.6.)	Triple-glazing (1 low- emissivity coating, 2 gaps with argon gas, and integral draught proofing/stripping, to achieve a U-value of 0.8 (Gustavsson, 2010))
	H/system	Conventional oil boiler	Condensing boiler, Solar hot water - 4m2 solar flat plate system	Ground source heat pump (Gshp), Solar hot water - 4m^2 solar flat plate system, Mechanical ventilation plus heat recovery (MVHR) and PV system

*DHW cylinder lagging jacket

Description of representative variables

Variable (m^2)	Quantity
Wall area	46
Roof area	47
Floor area	100
DHW insulation area	2
Window size	14

11. Detailed description of the retrofit measures applied to archetype 12 relative to the BaseCase scenario

Archetype 12		Scenario		
		BaseCase	**Current Regulations**	**Passive House standard**
Materials	**Building element**	**Existing information as above**	**Derivation of new retrofit measures relative to the BaseCase scenario**	
Mineral wool (slab)	Wall insulation	75(mm, thick)	125 kg	242 kg
Mineral wool (quilt)	Roof insulation	110(mm, thick)	84.5 kg	153 kg
Polyurethane rigid foam insulation	Ground floor	50(mm, thick)	210 kg	420 kg
Polyurethane rigid foam insulation	DHW cylinder insulation	30*(mm, thick)	1.2 kg	2.7kg
Polyurethane rigid foam insulation	Door insulation	0	3.53 kg	3.53 kg
	Air change rate	0.87ac/h	0.35 ac/h	0.25 ac/h
	Windows	Double-glazing	Triple-glazing (1 low-emissivity coating, 2 gaps with air to achieve a U-value of 1.6.)	Triple-glazing (1 low- emissivity coating, 2 gaps with argon gas, and integral draught proofing/stripping, to achieve a U-value of 0.8 (Gustavsson, 2010)
	H/system	Conventional oil boiler	Condensing boiler, Solar hot water - 4m2 solar flat plate system	Ground source heat pump (Gshp), Solar hot water - 4m^2 solar flat plate system, Mechanical ventilation plus heat recovery (MVHR) and PV system

*DHW cylinder lagging jacket

Description of representative variables

Variable (m^2)	Quantity
Wall area	47
Roof area	44
Floor area	100
DHW insulation area	2
Window size	13

12. **Detailed description of the retrofit measures applied to archetype 13 relative to the BaseCase scenario**

Archetype 13		**Scenario**		
		BaseCase	**Current Regulations**	**Passive House standard**
Materials	**Building element**	**Existing information as above**	**Derivation of new retrofit measures relative to the BaseCase scenario**	
Mineral wool (slab)	Wall insulation	0	193.5 kg	301 kg
Mineral wool (quilt)	Roof insulation	80(mm, thick)	111.7 kg	188.2 kg
Polyurethane rigid foam insulation	Ground floor	43(mm, thick)	307 kg	586.5 kg
Polyurethane rigid foam insulation	DHW cylinder insulation	35 (mm, thick)	0.9 kg	2.5kg
Polyurethane rigid foam insulation	Door insulation	0	3.53 kg	3.53 kg
	Air change rate	0.94ac/h	0.35 ac/h	0.25 ac/h
	Windows	Double-glazing	Triple-glazing (1 low-emissivity coating, 2 gaps with air to achieve a U-value of 1.6.)	Triple-glazing (1 low- emissivity coating, 2 gaps with argon gas, and integral draught proofing/stripping, to achieve a U-value of 0.8 (Gustavsson, 2010)
	H/system	Conventional oil boiler	Condensing boiler, Solar hot water - 4m^2 solar flat plate system	Ground source heat pump (Gshp), Solar hot water - 4m^2 solar flat plate system, Mechanical ventilation plus heat recovery (MVHR) and PV system

Description of representative variables

Variable (m^2)	Quantity
Wall area	43
Roof area	49
Floor area	133
DHW insulation area	2
Window size	19

Appendix 5: Bill of quantities

1. Bill of quantities for Archetype 1 BaseCase scenario

Category of upgrade	Upgrade description	Quantity	Units	Unit costs(€)	Total cost (€)	Labour cost (€)	Profits and Overheads (€)	Retrofit services cost (€)	Maintenance services cost (€)	Retrofit total cost (€)	Maintenance total cost (€)	Operational cost (€)	Disassembly cost (€)	Total life cycle costing	References
	Conventional oil-fired boiler due to ordinary replacement	2	Nr	2,250	4,500	1,360	631		1,991		6,491			6,491	Spon (2008)
	BOS to conventional boiler (pipes, etc)	1	Nr	450	450										Spon (2011)
	Water pump to conventional system (2 life cycle replacement) due to ordinary replacement	2	Nr	1,447	2,894	900	379		1,279		4,173			4,173	Spon (2011)
	Cabling to appliances and equipment	1	Nr	350	350				0		350			350	Spon (2008)
Heating system	Annual servicing of boiler	49	yr	100	4,900	4,900			4,900		9,800				
Sub-total (€)					**13,094**	**7,160**	**1,010**	**0**	**8,170**	**0**	**20,814**	**0**	**0**	**11,014**	
	Internal redecoration (includes painting to plasterboard background every 7 years) due to ordinary maintenance	966	m^2	3.1	3,004	800	380		1,180		4,185			4,185	Spon (2008)
Redecoration	External redecoration (includes painting to concrete background every 10 years) due to ordinary maintenance	644	m^2	3.6	2,338	900	324		1,224		3,561			3,561	Spon (2008)
Sub-total (€)					**5,342**	**1,700**	**704**	**0**	**2,404**		**7,746**		**0**	**7,746**	
	Electricity (include all taxes as at 2005)	5,506	kWh/yr	0.143	787							787		787	Finfacts.i.e (2012)
Operational energy	Oil (include all taxes and transportation as at 2005)	30,507	kWh/yr	0.075	2,297							2,297		2,297	Finfacts.i.e (2012)
Sub-total (€)					**3,085**	**0**	**0**	**0**	**0**			**3,085**	**0**	**3,085**	
Disassembly	Demolition at disassembly (cost of doing the work)	133	m^2	11.84		1,575	252						1,827	1,827	Building Journal: Demolition Cost Calculator (2012)
	Transportation, loading and disposal cost of materials of disassembly	104.74	tonne	54		5,656	566						6,222	6,222	
Sub-total (€)					**0**	**7,231**	**818**	**0**	**0**	**0**	**0**	**0**	**8,048**	**8,048**	
Total (€)					21,521	16,091	2,532	0	10,575	0	28,561	3,085	8,048	29,893	

2. Bill of quantities for Archetype 1 Current Regulations scenario

Category of upgrade	Upgrade description	Quantity	Units	Unit costs(€)	Total cost (€)	Labour cost (€)	Profits and Overheads (€)	Retrofit services cost (€)	Maintenance services cost (€)	Retrofit total cost (€)	Maintenance total cost (€)	Operational cost (€)	Disassembly cost (€)	Total life cycle costing	References
Wall improvement	Wall dry-lining (including timber studs, moisture membrane, plasterboard and painting)	161	m^2	11.3	1,821	1,051	287	1,339		3,159				3,159	Spon (2008)
	100mm mineral wool (slab) insulation	161	m^2	2.4	378	298	68	365		744				744	EST (2010)
Sub-total (€)					**2,199**	**1,349**	**355**	**1,704**	**0**	**3,903**	**0**	**0**	**0**	**3,903**	
Roof	150mm mineral wool (quilt) roof insulation	115	m^2	2.4	270	213	48	261		531				531	EST (2010)
Sub-total (€)					**270**	**213**	**48**	**261**	**0**	**531**	**0**	**0**	**0**	**531**	
Floor insulation	Removal of existing floor T&G and concrete slab	133	m^2	6.3		2,913	291	3,204		3,204				3,204	Spon (2008)
	65mm Polyurethane foam floor insulation	133	m^2	5.8	771	326	110	436		1,207				1,207	EST (2010)
	100mm thick new in-situ concrete floor	13.3	m^3	120.5	1,603	737	144	882		2,484				2,484	Spon (2008)
	50mm screed to new in-situ concrete floor	133	m^2	4.9	652	665	132	797		1,448				1,448	Spon (2008)
	Reinstallation of 18mm T&G floor boards	133	m^2	32.8	4,366	1,420	579	1,999		6,366				6,366	Spon (2008)
Sub-total (€)					**7,392**	**6,061**	**1,256**	**7,317**	**0**	**14,709**	**0**	**0**	**0**	**14,709**	
Windows and doors	Factory triple-glazed UPVC window due to retrofit	30	m^2	655.6	19,668	8,115	2,778	10,893		30,561				30,561	Spon (2008)
	A new 839x1981 mm entrance door with ironmongery	1	Nr	729.8	730	452	118	570		1,300				1,300	Spon (2008)
	25mm thick polyurethane insulation upgrade to door	1.66	m^2	5.8	10	58	7	65		75				75	
Sub-total (€)					**20,407**	**8,625**	**2,903**	**11,528**	**0**	**31,936**	**0**	**0**	**0**	**31,936**	
Heating system	Condensing, instantaneous boiler due to retrofit	1	Nr	2,250.0	2,250	680	338	1,018		3,268				3,268	Spon (2008)
	Condensing, instantaneous boiler due to ordinary replacement	2	Nr	2,250.0	4,500	1,360	586		1,946		6,446			6,446	Spon (2008)
	BOS to condensing boiler (pipes, etc)	1	Nr	450.0				450		450				450	Spon (2011)
	Annual servicing of condensing boiler	49	Yr	100.0		4,900			4,900		4,900			4,900	Bordgais, Ireland

Category of upgrade	Upgrade description	Quantity	Units	Unit costs(€)	Total cost (€)	Labour cost (€)	Profits and Overheads (€)	Retrofit services cost (€)	Maintenance services cost (€)	Retrofit total cost (€)	Maintenance total cost (€)	Operational cost (€)	Disassembly cost (€)	Total life cycle costing	References
	Water pump to conventional system (2 life cycle replacement) due to ordinary replacement	2	Nr	1,447.0	2,894	900	379		1,279		4,173			4,173	Spon (2011)
	Cabling to appliances and equipment	1	Nr	2,200.0	2,200									0	Spon (2008)
Sub-total (€)					**11,844**	**7,840**	**1,303**	**1,468**	**8,125**	**3,718**	**15,519**	**0**	**0**	**19,237**	
	BOS (tank, pump, etc) for Solar Water Heater + installation due to retrofit	1	Nr	2,312.0	2,312	1,120	440	1,560		3,872				3,872	Ayompe et al (2010)
	2 Solar flat plates due to retrofit	1	Nr	968.0	968			0		968				968	Ayompe et al (2010)
	BOS (tank, pump, etc) for Solar Water Heater + installation due to ordinary replacement	1	Nr	2,312.0	2,312	1,120	440		1,560		3,872			3,872	Ayompe et al (2010)
Renewable sources	2 Solar flat plates due to ordinary replacement	1	Nr	968.0	968			0		968				968	Ayompe et al (2010)
Sub-total (€)					**6,560**	**2,240**	**880**	**1,560**	**1,560**	**5,808**	**3,872**	**0**	**0**	**9,680**	
	External redecoration (includes painting to concrete background every 7 years) due to ordinary maintenance	644	m^2	3.1	2,003	800	280		1,080		3,083			3,083	Spon (2008)
Redecoration	Internal redecoration (includes painting to plasterboard background every 10 years) due to ordinary maintenance	966	m^2	3.6	3,507	900	441		1,341		4,847			4,847	Spon (2008)
Sub-total (€)					**5,509**	**1,700**	**721**	**0**	**2,421**	**0**	**7,930**	**0**	**0**	**7,930**	
	Electricity (include all taxes as at 2005)	48,54.5	kWh/yr	0.143	694							694		694	Finfacts.ie
Operational energy	Natural gas (ESB) (include carbon tax and vat)	30,507	kWh/yr	0.048	1,460	85	209					1,753		1,753	Bordgais
Sub-total (€)					**2,154**	**85**	**209**	**0**	**0**	**0**	**0**	**2,447**	**0**	**2,447**	
Demolition at disassembly		133	m^2	11.84		1575	252						1827	1,827	Building Journal: Demolition Cost Calculator (2012)
Transportation, loading and disposal cost of materials of disassembly		141.6	tonne	54		7646	765						8411	8,411	
Sub-total (€)					**0**	**9,221**	**1,017**	**0**	**0**	**0**	**0**	**0**	**10,238**	**10,238**	
Total (€)					56,067	27,900	7,626	23,577	12,106	60,074	27,322	2,447	10,238	**100,081**	

3. Bill of quantities for Archetype 1 Passive House scenario

Category of upgrade	Upgrade description	Quantity	Units	Unit costs(€)	Total cost (€)	Labour cost (€)	Profits and Overheads (€)	Retrofit services cost (€)	Maintenance services cost (€)	Retrofit total cost (Retrofit total cost) (€)	Maintenance total cost (€)	Operational cost (€)	Disassembly cost (€)	Total life cycle costing	References
Wall improvement	Wall dry-lining (including timber studs, moisture membrane, plasterboard and painting)	161	m^2	11.3	1,821	1,051	287	1,339		3,159				3,159	Spon (2008)
	100mm mineral wool (slab) insulation	161	m^2	2.4	378	298	68	365		744				744	EST (2010)
Sub-total (€)					**2,199**	**1,349**	**355**	**1,704**	**0**	**3,903**	**0**	**0**	**0**	**3,903**	
Roof	150mm mineral wool (quilt) roof insulation	115	m^2	2.4	270	213	48	261		531				531	EST (2010)
Sub-total (€)					**270**	**213**	**48**	**261**	**0**	**531**	**0**	**0**	**0**		
Floor insulation	Removal of existing floor T&G and concrete slab	133	m^2	6.3		2,913	291	3,204		3,204				3,204	Spon (2008)
	65mm Polyurethane foam floor insulation	133	m^2	5.8	771	326	110	436		1,207				1,207	EST (2010)
	100mm thick new in-situ concrete floor	13.3	m^3	120.5	1,603	737	144	882		2,484				2,484	Spon (2008)
	50mm screed to new in-situ concrete floor	133	m^2	4.9	652	665	132	797		1,448				1,448	Spon (2008)
	Reinstallation of 18mm T&G floor boards	133	m^2	32.8	4,366	1,420	579	1,999		6,366				6,366	Spon (2008)
Sub-total (€)					**7,392**	**6,061**	**1,256**	**7,317**	**0**	**14,709**	**0**	**0**	**0**	**14,709**	
Windows and doors	Factory triple-glazed UPVC window due to retrofit	30	m^2	655.6	19,668	8,115	2,778	10,893		30,561				30,561	Spon (2008)
	A new 839x1981 mm entrance door with ironmongery	1	Nr	729.8	730	452	118	570		1,300				1,300	Spon (2008)
	25mm thick polyurethane insulation upgrade to door	1.66	m^2	5.8	10	58	7	65		75				75	
Sub-total (€)					**20,407**	**8,625**	**2,903**	**11,528**	**0**	**31,936**	**0**	**0**	**0**	**31,936**	
Heating system	Vertical Ground Source Heat Pump (8kW) due to retrofit (about 60% efficient than ashp(Spon, 2008): include the cost for the unit and all associated pipe-work (50metre polyethylene pipe - EST, 2007)	1	Nr	12,500.0	12,500	6,240	2,498	8,738		21,238				21,238	Spon (2011)

Category of upgrade	Upgrade description	Quantity	Units	Unit costs(€)	Total cost (€)	Labour cost (€)	Profits and Overheads (€)	Retrofit services cost (€)	Maintenance services cost (€)	Retrofit total cost (Retrofit total cost) (€)	Maintenance total cost (€)	Operational cost (€)	Disassembly cost (€)	Total life cycle costing	References
	Ordinary replacement of compressors (scroll compressors)	1	Nr	400.0	400	600	100		700		1,100			1,100	EST, 2007
	Ordinary replacement of loop circulating pump	2	Nr	120.0	240	400	64		464		704			704	EST, 2007
	Occasional servicing of refrigerant of gshp for leakage (there is no annual mandatory servicing)	15	Nr	280.0		4,200			4,200		4,200			4,200	
	Mechanical Ventilation + Heat Recovery due to retrofit	1	Nr	4,200.0	4,200	800	860	1,660		5,860				5,860	Spon (2011)
	Mechanical Ventilation + Heat Recovery due to ordinary replacement	2	Nr	4,200.0	8,400	1,600	2,372		3,972		12,372			12,372	Spon (2011)
	BOS for Ventilation unit (air filters with fans, drain pan, air ducts, controls and exhaust fans)	2	Nr	1,800.0	3,600						3,600			3,600	Spon (2011)
	Annual replacement of filters for the ventilation unit	49	Yr	280.0	13,720	4,900	1,862		6,762		20,482			20,482	Spon (2011)
	Cabling to appliances and equipment	1	Nr	2,800.0	2,800						2,800			2,800	Spon (2008)
Sub-total (€)					**45,860**	**18,740**	**7,756**	**10,398**	**16,098**	**27,098**	**45,258**	**0**	**0**	**72,356**	
	BOS (tank, pump, etc) for Solar Water Heater + installation due to retrofit	1	Nr	2,312.0	2,312	1,120	440	1,560		3,872				3,872	Ayompe et al (2010)
	2 Solar flat plates due to retrofit	1	Nr	968.0	968			0		968				968	Ayompe et al (2010)
	BOS (tank, pump, etc) for Solar Water Heater + installation due to ordinary replacement	1	Nr	2,312.0	2,312	1,120	440		1,560		3,872			3,872	Ayompe et al (2010)
	2 Solar flat plates due to ordinary replacement	1	Nr	968.0	968			0			968			968	Ayompe et al (2010)
	Mono-crystal PV system (including 4 panels of approx. 2m2 each and BOS) due to retrofit to generate 943kWh/yr at max 1kwp	8	m^2	1,280.0	10,240	1,200	1,144	2,344		12,584					Spon (2011)
Renewable sources	Mono-crystal PV system (including 4 panels of approx. 2m2 each and BOS) due to replacement to generate 943kWh/yr at max 1kwp	8	m2	1,280.0	10,240	1,200	1,144		2,344		12,584				Spon (2011)
Sub-total (€)					**27,040**	**4,640**	**3,168**	**3,904**	**3,904**	**17,424**	**17,424**	**0**	**0**	**34,848**	
Redecoration															
	Internal redecoration (includes painting to plasterboard background every 7 years) due to	966	m^2	3.1	3,004	800	380		1,180		4,185			4,185	Spon (2008)

Category of upgrade	Upgrade description	Quantity	Units	Unit costs(€)	Total cost (€)	Labour cost (€)	Profits and Overheads (€)	Retrofit services cost (€)	Maintenance services cost (€)	Retrofit total cost (Retrofit total cost) (€)	Maintenance total cost (€)	Operational cost (€)	Disassembly cost (€)	Total life cycle costing	References
	ordinary maintenance														
	External redecoration (includes painting to concrete background every 10 years) due to ordinary maintenance	644	m^2	3.6	2,338	900	324		1,224		3,561			3,561	Spon (2008)
Sub-total (€)					**5,342**	**1,700**	**704**	**0**	**2,404**	**0**	**7,746**	**0**	**0**	**7,746**	
Operational energy	Electricity (include all taxes as at 2005)	44,42.2	kWh/yr	0.143	635							635		635	Finfacts.i.e (2012)
	No fossil fuels	0	kWh/yr	0.075	0							0		0	
Sub-total (€)					**635**	**0**	**0**	**0**	**0**	**0**	**0**	**635**	**0**	**635**	
Disassembly	Demolition at disassembly	133	m^2	11.84		1,575	252						1,827	1,827	Building Journal: Demolition Cost Calculator (2012)
	Transportation, loading and disposal cost of materials of disassembly	142.14	tonne	54		7,676	768						8,443	8,443	
Sub-total (€)						**9,250**	**1,020**	**0**	**0**	**0**	**0**	**0**	**10,270**	**10,270**	
Total (€)					108,876	41,115	16,142	34,851	22,406	95,070	70,428	635	10,270	**176,403**	

4. Bill of quantities for Archetype 7 BaseCase scenario

Category of upgrade	Upgrade description	Quantity	Units	Unit costs(€)	Total cost (€)	Labour cost (€)	Profits and Overheads (€)	Retrofit services cost (€)	Maintenance services cost (€)	Retrofit total cost (€)	Maintenance total cost (€)	Operational cost (€)	Disassembly cost (€)	Total life cycle costing	References
	Conventional oil-fired boiler due to ordinary replacement	2	Nr	2,250	4,500	1,360	631		1,991		6,491			6,491	Spon (2008)
	BOS to conventional boiler (pipes, etc)	1	Nr	450	450										Spon (2011)
	Water pump to conventional system (2 life cycle replacement) due to ordinary replacement	2	Nr	1,447	2,894	900	379		1,279		4,173			4,173	Spon (2011)
	Cabling to appliances and equipment	1	Nr	350	350				0		350			350	Spon (2008)
Heating systems	Annual servicing of boiler	49	yr	100	4,900	4,900			4,900		9,800				
Sub-total (€)					**13,094**	**7,160**	**1,010**	**0**	**8,170**	**0**	**20,814**	**0**	**0**	**11,014**	
	Internal redecoration (includes painting to plasterboard background every 7 years) due to ordinary maintenance	522	m^2	3.1	1,623	800	242		1,042		2,666			2,666	Spon (2008)
Redecoration	External redecoration (includes painting to concrete background every 10 years) due to ordinary maintenance	348	m^2	3.6	1,263	900	216		1,116		2,380			2,380	Spon (2008)
Sub-total (€)					**2,887**	**1,700**	**459**	**0**	**2,159**		**5,045**		**0**	**5,045**	
	Electricity (include all taxes as at 2005)	3,960	kWh/yr	0.143	566							566		566	Finfacts.i.e (2012)
Operational energy	Natural gas (ESB) (include carbon tax and vat)	19,222	kWh/yr	0.048	920							920		920	Bordgais, Ireland
Sub-total (€)					**1,486**	**0**	**0**	**0**	**0**			**1,486**	**0**	**1,486**	
Disassembly	Demolition at disassembly (cost of doing the work)	100	m^2	11.84		1,184	189						1,373	1,373	Building Journal: Demolition Cost Calculator (2012)
	Transportation, loading and disposal cost of materials of disassembly	78.74	tonne	54		4,252	425						4,677	4,677	USEPA, (2000)
Sub-total (€)					**0**	**5,436**	**615**	**0**	**0**	**0**	**0**	**0**	**6,051**	**6,051**	
Total (€)					17,467	14,296	2,084	0	10,329	0	25,860	1,486	6,051	23,597	

5. Bill of quantities for Archetype 7 Current Regulations scenario

Category of upgrade	Upgrade description	Quantity	Units	Unit costs(€)	Total cost (€)	Labour cost (€)	Profits and Overheads (€)	Retrofit services cost (€)	Maintenance services cost (€)	Retrofit total cost (€)	Maintenance total cost (€)	Operational cost (€)	Disassembly cost (€)	Total life cycle costing	References
	Wall dry-lining (including timber studs, moisture membrane, plasterboard and painting)	87	m^2	11.3	984	568	155	723		1,707				1,707	Spon (2008)
Wall improvement	100mm mineral wool (slab) insulation	87	m^2	2.4	204	161	37	197		402				402	EST (2010)
Sub-total (€)					**1,188**	**729**	**192**	**921**	**0**	**2,109**	**0**	**0**	**0**	**2,109**	
Roof	150mm mineral wool (quilt) roof insulation	55	m^2	2.4	129	102	23	125		254				254	EST (2010)
Sub-total (€)					**129**	**102**	**23**	**125**	**0**	**254**	**0**	**0**	**0**	**254**	
	Removal of existing floor T&G and concrete slab	100	m^2	6.3		2,190	219	2,409		2,409				2,409	Spon (2008)
	65mm Polyurethane foam floor insulation	100	m^2	5.8	580	245	83	328		908				908	EST (2010)
	100mm thick new in-situ concrete floor	10	m^3	120.5	1,205	554	113	667		1,873				1,873	Spon (2008)
	50mm screed to new in-situ concrete floor	100	m^2	4.9	490	500	99	599		1,089				1,089	Spon (2008)
Floor insulation	Reinstallation of 18mm T&G floor boards	100	m^2	32.8	3,283	1,068	435	1,503		4,786				4,786	Spon (2008)
Sub-total (€)					**5,558**	**4,557**	**949**	**5,506**	**0**	**11,064**	**0**	**0**	**0**	**11,064**	
	Factory triple-glazed UPVC window due to retrofit	17	m^2	655.6	11,145	4,599	1,574	6,173		17,318				17,318	Spon (2008)
	A new 839x1981 mm entrance door with ironmongery	1	Nr	729.8	730	452	118	570		1,300				1,300	Spon (2008)
Windows and doors	25mm thick polyurethane insulation upgrade to door	1.66	m^2	5.8	10	58	7	65		75				75	

Category of upgrade	Upgrade description	Quantity	Units	Unit costs(€)	Total cost (€)	Labour cost (€)	Profits and Overheads (€)	Retrofit services cost (€)	Maintenance services cost (€)	Retrofit total cost (€)	Maintenance total cost (€)	Operational cost (€)	Disassembly cost (€)	Total life cycle costing	References
Sub-total (€)					**11,885**	**5,108**	**1,699**	**6,808**	**0**	**18,692**	**0**	**0**	**0**	**18,692**	
	Condensing, instantaneous boiler due to retrofit	1	Nr	2,250.0	2,250	680	338	1,018		3,268				3,268	Spon (2008)
	Condensing, instantaneous boiler due to ordinary replacement	2	Nr	2,250.0	4,500	1,360	586		1,946		6,446			6,446	Spon (2008)
	BOS to condensing boiler (pipes, etc)	1	Nr	450.0				450		450				450	Spon (2011)
	Annual servicing of condensing boiler	49	Yr	100.0		4,900			4,900		4,900			4,900	Bord Gas, Ireland
	Water pump to conventional system (2 life cycle replacement) due to ordinary replacement	2	Nr	1,447.0	2,894	900	379		1,279		4,173			4,173	Spon (2011)
Heating system	Cabling to appliances and equipment	1	Nr	2,200.0	2,200									0	Spon (2008)
Sub-total (€)					**11,844**	**7,840**	**1,303**	**1,468**	**8,125**	**3,718**	**15,519**	**0**	**0**	**19,237**	
	BOS (tank, pump, etc) for Solar Water Heater + installation due to retrofit	1	Nr	2,312.0	2,312	1,120	440	1,560		3,872				3,872	Ayompe et al (2010)
	2 Solar flat plates due to retrofit	1	Nr	968.0	968			0		968				968	Ayompe et al (2010)
	BOS (tank, pump, etc) for Solar Water Heater + installation due to ordinary replacement	1	Nr	2,312.0	2,312	1,120	440		1,560		3,872			3,872	Ayompe et al (2010)
Renewable sources	2 Solar flat plates due to ordinary replacement	1	Nr	968.0	968			0		968				968	Ayompe et al (2010)
Sub-total (€)					**6,560**	**2,240**	**880**	**1,560**	**1,560**	**5,808**	**3,872**	**0**	**0**	**9,680**	
Redecoration															
	Internal redecoration (includes painting to plasterboard background	522	m^2	3.1	1,623	800	242		1,042		2,666			2,666	Spon (2008)

Category of upgrade	Upgrade description	Quantity	Units	Unit costs(€)	Total cost (€)	Labour cost (€)	Profits and Overheads (€)	Retrofit services cost (€)	Maintenance services cost (€)	Retrofit total cost (€)	Maintenance total cost (€)	Operational cost (€)	Disassembly cost (€)	Total life cycle costing	References
	every 7 years) due to ordinary maintenance														
	External redecoration (includes painting to concrete background every 10 years) due to ordinary maintenance	348	m^2	3.6	1,263	900	216		1,116		2,380			2,380	Spon (2008)
Sub-total (€)					**2,887**	**1,700**	**459**	**0**	**2,159**	**0**	**5,045**	**0**	**0**	**5,045**	
	Electricity (include all taxes as at 2005)	3,470	kWh/yr	0.143	496							496		496	Finfacts.i.e (2012)
Operational energy	Natural gas (ESB) (include carbon tax and vat)	7,367	kWh/yr	0.048	353	20	50					423		423	Bordgais, Ireland
Sub-total (€)					**849**	**20**	**50**	**0**	**0**	**0**	**0**	**920**	**0**	**920**	
Demolition at disassembly		100	m^2	11.84		1184	189						1373	1,373	Building Journal: Demolition Cost Calculator (2012)
Transportation, loading and disposal cost of materials of disassembly		85	tonne	54		4590	459						5049	5,049	USEPA, (2000)
Sub-total (€)					**0**	**5,774**	**648**	**0**	**0**	**0**	**0**	**0**	**6,422**	**6,422**	
Total (€)					40,771	22,195	5,532	16,263	11,844	41,392	24,437	920	6,422	**73,170**	

6. Bill of quantities for Archetype 7 Passive House scenario

Category of upgrade	Upgrade description	Quantity	Units	Unit costs(€)	Total cost (€)	Labour cost (€)	Profits and Overheads (€)	Retrofit services cost (€)	Maintenance services cost (€)	Retrofit total cost (Retrofit total cost) (€)	Maintenance total cost (€)	Operational cost (€)	Disassembly cost (€)	Total life cycle costing	References
Wall improvement	Wall dry-lining (including timber studs, moisture membrane, plasterboard and painting)	87	m^2	11.3	984	568	155	723		1,707				1,707	Spon (2008)
	100mm mineral wool (slab) insulation	87	m^2	2.4	204	161	37	197		402				402	EST (2010)
Sub-total (€)					**1,188**	**729**	**192**	**921**	**0**	**2,109**	**0**	**0**	**0**	**2,109**	
Roof	150mm mineral wool (quilt) roof insulation	55	m^2	2.4	129	102	23	125		254				254	EST (2010)
Sub-total (€)					**129**	**102**	**23**	**125**	**0**	**254**	**0**	**0**	**0**		
Floor insulation	Removal of existing floor T&G and concrete slab	100	m^2	6.3		2,190	219	2,409		2,409				2,409	Spon (2008)
	65mm Polyurethane foam floor insulation	100	m^2	5.8	580	245	83	328		908				908	EST (2010)
	100mm thick new in-situ concrete floor	10	m^3	120.5	1,205	554	113	667		1,873				1,873	Spon (2008)
	50mm screed to new in-situ concrete floor	100	m^2	4.9	490	500	99	599		1,089				1,089	Spon (2008)
	Reinstallation of 18mm T&G floor boards	100	m^2	32.8	3,283	1,068	435	1,503		4,786				4,786	Spon (2008)
Sub-total (€)					**5,558**	**4,557**	**949**	**5,506**	**0**	**11,064**	**0**	**0**	**0**	**11,064**	
Windows and doors	Factory triple-glazed UPVC window due to retrofit	17	m^2	655.6	11,145	4,599	1,574	6,173		17,318				17,318	Spon (2008)
	A new 839x1981 mm entrance door with ironmongery	1	Nr	729.8	730	452	118	570		1,300				1,300	Spon (2008)
	25mm thick polyurethane insulation upgrade to door	1.66	m^2	5.8	10	58	7	65		75				75	
Sub-total (€)					**11,885**	**5,108**	**1,699**	**6,808**	**0**	**18,692**	**0**	**0**	**0**	**18,692**	
Heating system															
	Vertical Ground Source Heat Pump (8kW) due to retrofit (about 60% efficient than ashp(Spon,	1	Nr	12,500.0	12,500	6,240	2,498	8,738		21,238				21,238	Spon (2011)

Category of upgrade	Upgrade description	Quantity	Units	Unit costs(€)	Total cost (€)	Labour cost (€)	Profits and Overheads (€)	Retrofit services cost (€)	Maintenance services cost (€)	Retrofit total cost (Retrofit total cost) (€)	Maintenance total cost (€)	Operational cost (€)	Disassembly cost (€)	Total life cycle costing	References
	2008): include the cost for the unit and all associated pipe-work (50metre polyethylene pipe - EST, 2007)														
	Ordinary replacement of compressors (scroll compressors)	1	Nr	400.0	400	600	100		700		1,100			1,100	EST, 2007
	Ordinary replacement of loop circulating pump	2	Nr	120.0	240	400	64		464		704			704	EST, 2007
	Occasional servicing of refrigerant of gshp for leakage (there is no annual mandatory servicing)	15	Nr	280.0		4,200			4,200		4,200			4,200	
	Mechanical Ventilation + Heat Recovery due to retrofit	1	Nr	4,200.0	4,200	800	860	1,660		5,860				5,860	Spon (2011)
	Mechanical Ventilation + Heat Recovery due to ordinary replacement	2	Nr	4,200.0	8,400	1,600	2,372		3,972		12,372			12,372	Spon (2011)
	BOS for Ventilation unit (air filters with fans, drain pan, air ducts, controls and exhaust fans)	2	Nr	1,800.0	3,600						3,600			3,600	Spon (2011)
	Annual replacement of filters for the ventilation unit	49	Yr	280.0	13,720	4,900	1,862		6,762		20,482			20,482	Spon (2011)
	Cabling to appliances and equipment	1	Nr	2,800.0	2,800						2,800			2,800	Spon (2008)
Sub-total (€)					**45,860**	**18,740**	**7,756**	**10,398**	**16,098**	**27,098**	**45,258**	**0**	**0**	**72,356**	
Renewable sources	BOS (tank, pump, etc) for Solar Water Heater + installation due to retrofit	1	Nr	2,312.0	2,312	1,120	440	1,560		3,872				3,872	Ayompe et al (2010)
	2 Solar flat plates due to retrofit	1	Nr	968.0	968			0		968				968	Ayompe et al (2010)
	BOS (tank, pump, etc) for Solar Water Heater + installation due to ordinary replacement	1	Nr	2,312.0	2,312	1,120	440		1,560		3,872			3,872	Ayompe et al (2010)
	2 Solar flat plates due to ordinary replacement	1	Nr	968.0	968			0			968			968	Ayompe et al (2010)
	Mono-crystal PV system (including 4 panels of approx. 2m2 each and BOS) due to retrofit to generate 943kWh/yr at max 1kwp	8	m^2	1,280.0	10,240	1,200	1,144	2,344		12,584					Spon (2011)

Category of upgrade	Upgrade description	Quantity	Units	Unit costs(€)	Total cost (€)	Labour cost (€)	Profits and Overheads (€)	Retrofit services cost (€)	Maintenance services cost (€)	Retrofit total cost (Retrofit total cost) (€)	Maintenance total cost (€)	Operational cost (€)	Disassembly cost (€)	Total life cycle costing	References
	Mono-crystal PV system (including 4 panels of approx. 2m2 each and BOS) due to replacement to generate 943kWh/yr at max 1kwp	8	m^2	1,280.0	10,240	1,200	1,144		2,344		12,584				Spon (2011)
Sub-total (€)					**27,040**	**4,640**	**3,168**	**3,904**	**3,904**	**17,424**	**17,424**	**0**	**0**	**34,848**	
	Internal redecoration (includes painting to plasterboard background every 7 years) due to ordinary maintenance	522	m^2	3.1	1,623	800	242		1,042		2,666			2,666	Spon (2008)
Redecoration	External redecoration (includes painting to concrete background every 10 years) due to ordinary maintenance	348	m^2	3.6	1,263	900	216		1,116		2,380			2,380	Spon (2008)
Sub-total (€)					**2,887**	**1,700**	**459**	**0**	**2,159**	**0**	**5,045**	**0**	**0**	**5,045**	
Operational energy	Electricity (include all taxes as at 2005)	4210	kWh/yr	0.143	602							602		602	Finfacts.i.e (2012)
	Oil (include all taxes as at 2005)	0	kWh/yr	0.075	0							0		0	
Sub-total (€)					**602**	**0**	**0**	**0**	**0**	**0**	**0**	**602**	**0**	**602**	
	Demolition at disassembly	100	m^2	11.84		1,184	189						1,373	1,373	Building Journal: Demolition Cost Calculator (2012)
Disassembly	Transportation, loading and disposal cost of materials of disassembly	85.9	tonne	54		4,639	464						5,102	5,102	USEPA, (2000)
Sub-total (€)						**5,823**	**653**	**0**	**0**	**0**	**0**	**0**	**6,476**	**6,476**	
Total (€)					95,020	35,475	14,222	27,537	22,161	76,388	67,727	602	6,476	**151,193**	

7. Bill of quantities for Archetype 11 BaseCase scenario

Category of upgrade	Upgrade description	Quantity	Units	Unit costs(€)	Total cost (€)	Labour cost (€)	Profits and Overheads (€)	Retrofit services cost (€)	Maintenance services cost (€)	Retrofit total cost (€)	Maintenance total cost (€)	Operational cost (€)	Disassembly cost (€)	Total life cycle costing	References
	Conventional oil-fired boiler due to ordinary replacement	2	Nr	2,250	4,500	1,360	631		1,991		6,491			6,491	Spon (2008)
	BOS to conventional boiler (pipes, etc)	1	Nr	450	450										Spon (2011)
	Water pump to conventional system (2 life cycle replacement) due to ordinary replacement	2	Nr	1,447	2,894	900	379		1,279		4,173			4,173	Spon (2011)
	Cabling to appliances and equipment	1	Nr	350	350				0		350			350	Spon (2008)
Heating systems	Annual servicing of boiler	49	yr	100	4,900	4,900			4,900		9,800				
Sub-total (€)					**13,094**	**7,160**	**1,010**	**0**	**8,170**	**0**	**20,814**	**0**	**0**	**11,014**	
	Internal redecoration (includes painting to plasterboard background every 7 years) due to ordinary maintenance	276	m^2	3.1	858	400	126		526		1,384			1,384	Spon (2008)
Redecoration	External redecoration (includes painting to concrete background every 10 years) due to ordinary maintenance	184	m^2	3.6	668	500	117		617		1,285			1,285	Spon (2008)
Sub-total (€)					**1,526**	**900**	**243**	**0**	**1,143**		**2,669**		**0**	**2,669**	
	Electricity (include all taxes as at 2005)	3,800	kWh/yr	0.143	543							543		543	Finfacts.i.e (2012)
Operational energy	Natural gas (ESB) (include carbon tax and vat)	17,011	kWh/yr	0.048	814							814		814	Bordgais, Ireland
Sub-total (€)					**1,358**	**0**	**0**	**0**	**0**			**1,358**	**0**	**1,358**	
Disassembly	Demolition at disassembly (cost of doing the work)	100	m^2	11.84		1,184	189						1,373	1,373	Building Journal: Demolition Cost Calculator (2012)
	Transportation, loading and disposal cost of materials of disassembly	78.67	tonne	54		4,248	425						4,673	4,673	USEPA, (2000)
Sub-total (€)					**0**	**5,432**	**614**	**0**	**0**	**0**	**0**	**0**	**6,046**	**6,046**	
Total (€)					**15,978**	**13,492**	**1,867**	**0**	**9,313**	**0**	**23,483**	**1,358**	**6,046**	**21,087**	

8. Bill of quantities for Archetype 11 Current Regulations scenario

Category of upgrade	Upgrade description	Quantity	Units	Unit costs(€)	Total cost (€)	Labour cost (€)	Profits and Overheads (€)	Retrofit services cost (€)	Maintenance services cost (€)	Retrofit total cost (€)	Maintenance total cost (€)	Operational cost (€)	Disassembly cost (€)	Total life cycle costing	References
Wall improvement	Wall dry-lining (including timber studs, moisture membrane, plasterboard and painting)	46	m^2	11.3	520	300	82	382		903				903	Spon (2008)
	100mm mineral wool (slab) insulation	46	m^2	2.4	108	85	19	104		213				213	EST (2010)
Sub-total (€)					**628**	**385**	**101**	**487**	**0**	**1,115**	**0**	**0**	**0**	**1,115**	
Roof	150mm mineral wool (quilt) roof insulation	47	m^2	2.4	110	87	20	107		217				217	EST (2010)
Sub-total (€)					**110**	**87**	**20**	**107**	**0**	**217**	**0**	**0**	**0**	**217**	
Floor insulation	Removal of existing floor T&G and concrete slab	100	m^2	6.3		2,190	219	2,409		2,409				2,409	Spon (2008)
	65mm Polyurethane foam floor insulation	100	m^2	5.8	580	245	83	328		908				908	EST (2010)
	100mm thick new in-situ concrete floor	10	m^3	120.5	1,205	554	113	667		1,873				1,873	Spon (2008)
	50mm screed to new in-situ concrete floor	100	m^2	4.9	490	500	99	599		1,089				1,089	Spon (2008)
	Reinstallation of 18mm T&G floor boards	100	m^2	32.8	3,283	1,068	435	1,503		4,786				4,786	Spon (2008)
Sub-total (€)					**5,558**	**4,557**	**949**	**5,506**	**0**	**11,064**	**0**	**0**	**0**	**11,064**	
Windows and doors	Factory triple-glazed UPVC window due to retrofit	14	m^2	655.6	9,178	3,787	1,297	5,084		14,262				14,262	Spon (2008)
	A new 839x1981 mm entrance door with ironmongery	1	Nr	729.8	730	452	118	570		1,300				1,300	Spon (2008)
	25mm thick polyurethane insulation upgrade to door	1.66	m^2	5.8	10	58	7	65		75				75	
Sub-total (€)					**9,918**	**4,297**	**1,421**	**5,718**	**0**	**15,636**	**0**	**0**	**0**	**15,636**	
Heating system	Condensing, instantaneous boiler due to retrofit	1	Nr	2,250.0	2,250	680	338	1,018		3,268				3,268	Spon (2008)
	Condensing, instantaneous boiler due to ordinary replacement	2	Nr	2,250.0	4,500	1,360	586		1,946		6,446			6,446	Spon (2008)
	BOS to condensing boiler (pipes, etc)	1	Nr	450.0				450		450				450	Spon (2011)
	Annual servicing of condensing boiler	49	Yr	100.0		4,900			4,900		4,900			4,900	Bord Gas, Ireland

Category of upgrade	Upgrade description	Quantity	Units	Unit costs(€)	Total cost (€)	Labour cost (€)	Profits and Overheads (€)	Retrofit services cost (€)	Maintenance services cost (€)	Retrofit total cost (€)	Maintenance total cost (€)	Operational cost (€)	Disassembly cost (€)	Total life cycle costing	References
	Water pump to conventional system (2 life cycle replacement) due to ordinary replacement	2	Nr	1,447.0	2,894	900	379		1,279		4,173			4,173	Spon (2011)
	Cabling to appliances and equipment	1	Nr	2,200.0	2,200									0	Spon (2008)
Sub-total (€)					**11,844**	**7,840**	**1,303**	**1,468**	**8,125**	**3,718**	**15,519**	**0**	**0**	**19,237**	
	BOS (tank, pump, etc) for Solar Water Heater + installation due to retrofit	1	Nr	2,312.0	2,312	1,120	440	1,560		3,872				3,872	Ayompe et al (2010)
	2 Solar flat plates due to retrofit	1	Nr	968.0	968			0		968				968	Ayompe et al (2010)
	BOS (tank, pump, etc) for Solar Water Heater + installation due to ordinary replacement	1	Nr	2,312.0	2,312	1,120	440		1,560		3,872			3,872	Ayompe et al (2010)
Renewable sources	2 Solar flat plates due to ordinary replacement	1	Nr	968.0	968			0		968				968	Ayompe et al (2010)
Sub-total (€)					**6,560**	**2,240**	**880**	**1,560**	**1,560**	**5,808**	**3,872**	**0**	**0**	**9,680**	
	Internal redecoration (includes painting to plasterboard background every 7 years) due to ordinary maintenance	276	m^2	3.1	858	1,515	237		1,753		2,611			2,611	Spon (2008)
Redecoration	External redecoration (includes painting to concrete background every 10 years) due to ordinary maintenance	184	m^2	3.6	668	1,095	176		1,271		1,939			1,939	Spon (2008)
Sub-total (€)					**1,526**	**2,610**	**414**	**0**	**3,024**	**0**	**4,550**	**0**	**0**	**4,550**	
	Electricity (include all taxes as at 2005)	3,410	kWh/yr	0.143	488							488		488	Finfacts.i.e (2012)
Operational energy	Natural gas (ESB) (include carbon tax and vat)	6,678	kWh/yr	0.048	320	18	46					384		384	Bordgais, Ireland
Sub-total (€)					**807**	**18**	**46**	**0**	**0**	**0**	**0**	**871**	**0**	**871**	
Demolition at disassembly		100	m^2	11.84		1184	189						1373	1,373	Building Journal: Demolition Cost Calculator (2012)
Transportation, loading and disposal cost of materials of disassembly		84.1	tonne	54		4541	454						4996	4,996	USEPA, (2000)
Sub-total (€)					**0**	**5,725**	**644**	**0**	**0**	**0**	**0**	**0**	**6,369**	**6,369**	
Total (€)					36,842	21,948	5,114	14,739	12,709	37,342	23,941	871	6,369	**68,523**	

9. Bill of quantities for Archetype 11 Passive House scenario

Category of upgrade	Upgrade description	Quantity	Units	Unit costs(€)	Total cost (€)	Labour cost (€)	Profits and Overheads (€)	Retrofit services cost (€)	Maintenance services cost (€)	Retrofit total cost (€)	Maintenance total cost (€)	Operational cost (€)	Disassembly cost (€)	Total life cycle costing	References
Wall improvement	Wall dry-lining (including timber studs, moisture membrane, plasterboard and painting)	46	m^2	11.3	520	300	82	382		903				903	Spon (2008)
	100mm mineral wool (slab) insulation	46	m^2	2.4	108	85	19	104		213				213	EST (2010)
Sub-total (€)					**628**	**385**	**101**	**487**	**0**	**1,115**	**0**	**0**	**0**	**1,115**	
Roof	150mm mineral wool (quilt) roof insulation	47	m^2	2.4	110	87	20	107		217				217	EST (2010)
Sub-total (€)					**110**	**87**	**20**	**107**	**0**	**217**	**0**	**0**	**0**		
Floor insulation	Removal of existing floor T&G and concrete slab	100	m^2	6.3		2,190	219	2,409		2,409				2,409	Spon (2008)
	65mm Polyurethane foam floor insulation	100	m^2	5.8	580	245	83	328		908				908	EST (2010)
	100mm thick new in-situ concrete floor	10	m^3	120.5	1,205	554	113	667		1,873				1,873	Spon (2008)
	50mm screed to new in-situ concrete floor	100	m^2	4.9	490	500	99	599		1,089				1,089	Spon (2008)
	Reinstallation of 18mm T&G floor boards	100	m^2	32.8	3,283	1,068	435	1,503		4,786				4,786	Spon (2008)
Sub-total (€)					**5,558**	**4,557**	**949**	**5,506**	**0**	**11,064**	**0**	**0**	**0**	**11,064**	
Windows and doors	Factory triple-glazed UPVC window due to retrofit	14	m^2	655.6	9,178	3,787	1,297	5,084		14,262				14,262	Spon (2008)
	A new 839x1981 mm entrance door with ironmongery	1	Nr	729.8	730	452	118	570		1,300				1,300	Spon (2008)
	25mm thick polyurethane insulation upgrade to door	1.66	m^2	5.8	10	58	7	65		75				75	
Sub-total (€)					**9,918**	**4,297**	**1,421**	**5,718**	**0**	**15,636**	**0**	**0**	**0**	**15,636**	
Heating system															
	Air Source Heat Pump (8kW) due to retrofit (about 60% efficient than ashp(Spon, 2008): include the cost for the unit and all associated pipe-work (50metre polyethylene	1	Nr	9,000.0	9,000	4,800	1,860	6,660		15,660				15,660	Spon (2011)

Category of upgrade	Upgrade description	Quantity	Units	Unit costs(€)	Total cost (€)	Labour cost (€)	Profits and Overheads (€)	Retrofit services cost (€)	Maintenance services cost (€)	Retrofit total cost (€)	Maintenance total cost (€)	Operational cost (€)	Disassembly cost (€)	Total life cycle costing	References
	pipe - EST, 2007)														
	Ordinary replacement of compressors	1	Nr	400.0	400	600	100		700		1,100			1,100	EST, 2007
	Ordinary replacement of loop circulating pump (not applicable here)		Nr	120.0	0		0		0		0			0	EST, 2007
	Occassional servicing of of refrigerant of gshp for leakage (there is no annual mandatory servicing)	15	Nr	280.0		4,200			4,200		4,200			4,200	
	Mechanical Ventilation + Heat Recovery due to retrofit	1	Nr	4,200.0	4,200	800	860	1,660		5,860				5,860	Spon (2011)
	Mechanical Ventilation + Heat Recovery due to ordinary replacement	2	Nr	4,200.0	8,400	1,600	2,372		3,972		12,372			12,372	Spon (2011)
	BOS for Ventilation unit (air filters with fans, drain pan, air ducts, controls and exhaust fans)	2	Nr	1,800.0	3,600						3,600			3,600	Spon (2011)
	Annual replacement of filters for the ventilation unit	49	Yr	280.0	13,720	4,900	1,862		6,762		20,482			20,482	Spon (2011)
	Cabling to appliances and equipment	1	Nr	2,800.0	2,800						2,800			2,800	Spon (2008)
Sub-total (€)					**42,120**	**16,900**	**7,054**	**8,320**	**15,634**	**21,520**	**44,554**	**0**	**0**	**66,074**	
	BOS (tank, pump, etc) for Solar Water Heater + installation due to retrofit	1	Nr	2,312.0	2,312	1,120	440	1,560		3,872				3,872	Ayompe et al, (2010)
	2 Solar flat plates due to retrofit	1	Nr	968.0	968			0		968				968	Ayompe et al, (2010)
	BOS (tank, pump, etc) for Solar Water Heater + installation due to ordinary replacement	1	Nr	2,312.0	2,312	1,120	440		1,560		3,872			3,872	Ayompe et al, (2010)
	2 Solar flat plates due to ordinary replacement	1	Nr	968.0	968			0			968			968	Ayompe et al, (2010)
	Mono-crystal PV system (including 4 panels of approx. 2m2 each and BOS) due to retrofit to generate 943kWh/yr at max 1kwp	8	m^2	1,280.0	10,240	1,200	1,144	2,344		12,584					Spon (2011)
Renewable sources	Mono-crystal PV system (including 4 panels of approx. 2m2	8	m^2	1,280.0	10,240	1,200	1,144		2,344		12,584				Spon (2011)

Category of upgrade	Upgrade description	Quantity	Units	Unit costs(€)	Total cost (€)	Labour cost (€)	Profits and Overheads (€)	Retrofit services cost (€)	Maintenance services cost (€)	Retrofit total cost (€)	Maintenance total cost (€)	Operational cost (€)	Disassembly cost (€)	Total life cycle costing	References
	each and BOS) due to replacement to generate 943kWh/yr at max 1kwp														
Sub-total (€)					**27,040**	**4,640**	**3,168**	**3,904**	**3,904**	**17,424**	**17,424**	**0**	**0**	**34,848**	
	Internal redecoration (includes painting to plasterboard background every 7 years) due to ordinary maintenance	276	m^2	3.1	858	1,515	237		1,753		2,611			2,611	Spon (2008)
Redecoration	External redecoration (includes painting to concrete background every 10 years) due to ordinary maintenance	184	m^2	3.6	668	1,095	176		1,271		1,939			1,939	Spon (2008)
Sub-total (€)					**1,526**	**2,610**	**414**	**0**	**3,024**	**0**	**4,550**	**0**	**0**	**4,550**	
Operational energy	Electricity (include all taxes as at 2005)	4300	kWh/yr	0.143	615							615		615	Finfacts.i.e (2012)
	Oil (include all taxes as at 2005)	0	kWh/yr	0.075	0							0		0	
Sub-total (€)					**615**	**0**	**0**	**0**	**0**	**0**	**0**	**615**	**0**	**615**	
	Demolition at disassembly	100	m^2	11.84		1,184	189						1,373	1,373	Building Journal: Demolition Cost Calculator (2012)
Disassembly	Transportation, loading and disposal cost of materials of disassembly	85.06	tonne	54		4,593	459						5,053	5,053	USEPA, (2000)
Sub-total (€)						**5,777**	**649**	**0**	**0**	**0**	**0**	**0**	**6,426**	**6,426**	
Total (€)					**87,406**	**33,390**	**13,107**	**23,935**	**22,562**	**66,760**	**66,528**	**615**	**6,426**	**140,328**	

Appendix 6: List of Publications

Journal Publication

- Famuyibo A. A., Duffy Aidan, Strachan Paul. Developing archetypes for domestic dwellings – An Irish case study; Energy and Buildings, vol. 50 (2012); pp784-791.

Journal Submissions: Under Review

- Famuyibo A. A., Duffy Aidan, Strachan Paul. A hybrid life cycle analysis of energy efficient refurbishment options for Irish housing (2012).

Conference Proceedings

- Famuyibo A. A., Duffy Aidan, Strachan Paul. A life cycle assessment of emissions reduction potential in the existing Irish housing stock: a perspective of international and domestic sources; Proceedings of SEEP2012, 05-08 June 2012, Dublin City University, Dublin, Ireland.

Working Paper

- Famuyibo, A. A. Duffy, Aidan P. and Paul Strachan (2012); Ireland's greenhouse gas emissions abatement opportunity for the years 2020 and 2050.